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DESIGN AND OPTIMISATION OF FOCUSED
INFRARED HEATING DEVICES

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Declaration

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Summary

This work presents a study into the design of focused infrared heaters (FIRHs) using Monte Carlo ray tracing (MCRT) and a genetic algorithm (GA) based optimisation strategy. IR heating technology delivers many advantages in comparison to alternative heating techniques due to the rapid response times and the ability to heat without contact between the source and target. Focused IR technology is a subset of this field which employs a reflector to direct the emitted IR radiation over a small area, allowing controlled heating of a target with higher intensities than otherwise possible. The conventional design strategies employed for FIRH technology are limited to trial-and-error based techniques using spheroidal and elliptic shapes conceived under the premise of a point source emission. Due to this assumption, the performance of commercially available devices and those found in the literature are severely limited and markedly below that of the theoretical maximum. Therefore, this thesis bridges the gap between the current performance of FIRHs and the proposed theoretical limits by developing a rigorous design methodology which can optimise a reflector which is bespoke to the size and shape of a given source. This is achieved using a combination of radiative numerical modelling, metaheuristic optimisation, and reflector shape parametrisation using Bézier splines.

The development of an optimised reflector specific to the IR source employed necessitates the understanding of the thermal performance of that source. The thermal performance of high-temperature quartz tungsten halogen (QTH) sources was not addressed adequately in the literature, and therefore, was investigated in this work. The approach taken was to characterise the radiative efficiency and radiative output distribution over a range of operating conditions. A link was drawn between the temperature of the filament and the radiative efficiency of the sources and an understanding was established for the mechanism which gives rise to the high thermal efficiencies of over 90%. A new efficiency curve was developed which will allow other researchers to estimate the efficiency of similar QTH lamps

through measurement of filament temperature. The results of this aspect of the research fed into the development of a numerical model that can assess the performance of a FIRH. The modelling approach adopted employed the MCRT technique to compute the effectiveness of a given reflector shape. A GA metaheuristic optimiser was used to navigate the search domain and converge on a custom reflector shape specific to source geometry. An optimised reflector was manufactured, characterised, and demonstrated to outperform commercially available FIRHs in terms of efficiency and heat flux output with a significantly smaller reflector size.

The 2D model was subsequently extended to a full 3D model which can account for the entire geometry of the source and reflector. A series of optimisations were performed using commonly employed QTH sources, which allows direct comparison to commercially available FIRHs. The optimised reflectors were found to provide considerable improvements in heat flux output and efficiency when compared to the market leaders in focused IR technology. Design strategies for specifying an outlet size are introduced based on nonimaging optics theory and the concepts of étendue and skewness differences between the source and target. A trade-off between efficiency and heat flux output was observed, which allows the design of FIRHs for various applications by the adjustment of the outlet size of the reflector relative to a fixed source geometry. It was found that a dilution-optimised reflector provided an ideal operating point to maximise heat flux intensity while maintaining an acceptable reflector efficiency; it is therefore recommended for FIRHs specifically designed for high heat flux applications. A method for specifying the outlet of a FIRH in order to maximise the heat flux and efficiency simultaneously is also provided.

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- R. Jenkins, B. Aldwell, W. Wits, A. J. Robinson & R. Lupoi. Geometric optimisation and characterisation of a focused infrared heater. In submission.
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- R. Jenkins, S. Yin, B. Aldwell, M. Meyer, & R. Lupoi, (2019). New insights into the in-process densification mechanism of cold spray Al coatings: Low deposition efficiency induced densification. Journal of materials science & technology, 35(3), 427-431. DOI: 10.1016/j.jmst.2018.09.045
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- S. Yin, P. Cavaliere, B. Aldwell, R. Jenkins, H. Liao, W. Li, & R. Lupoi, (2018). Cold spray additive manufacturing and repair: Fundamentals and applications. *Additive Manufacturing*, 21, 628-650. DOI: 10.1016/j.addma.2018.04.017
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Nomenclature

Roman Symbols

$\acute{E}$	Étendue ($\text{mm}^2 \text{ sr}$)
$\vec{N}$	Unit length normal vector
$\vec{T}$	Unit length tangent vector
$\vec{V}$	Unit length vector direction
A	Area (m^2)
b_i	Bernstein polynomial
C	Geometric concentration factor
c_0	The speed of light in a vacuum 2.9979×10^8 (m/s)
C_p	Heat capacity (J/K)
D	Diameter (m)
E	Emissive power (W/m^2)
G	Incident radiation intensity (W/m^2)
g	Gravitational constant 9.81 (m/s)
Gr	Grashof number
h	Heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$)
h	Planck constant 6.6256×10^{-34} (J.s)
I	Current (A)

J	Radiosity (W/m ²)
k	Thermal conductivity (W/mK)
k_b	The Boltzmann constant 1.38065×10^{-23} (J/K)
L	Length (m)
m	Mass (kg)
N	Number of rays
n	Refractive index
Nu	Nusselt number
P	Power (W)
P_i	Bézier control points
P_s	Phase space (mm ² sr)
Q	Rate of heat transfer (W)
q''	Heat flux (W/cm ²)
R	Resistance (Ω), Random number
r	Radius (m), Resistivity (Ω /m)
$R(t)$	Equation of a ray
Ra	Rayleigh number
S	Surface area (m ²)
T	Temperature (K)
U	Uncertainty
V	Voltage (V), Volume (m ³)

Abbreviations

$1D$, $2D$, $3D$	One, two, three-dimensional
--------------------	-----------------------------

<i>CFD</i>	Computational fluid dynamics
<i>CS</i>	Cold spray
<i>FIRH</i>	Focused infrared heater
<i>GA</i>	Genetic algorithm
<i>HFUF</i>	Heat flux utilisation factor
<i>IR</i>	Infrared
<i>MCRT</i>	Monte Carlo ray tracing
<i>NIO</i>	Nonimaging optics
<i>PCS</i>	Precision Control Systems
<i>PSO</i>	Particle swarm optimisation
<i>QTH</i>	Quartz tungsten halogen
<i>RDM</i>	Radial difference minimisation
<i>RT</i>	Ray tracing
<i>VDPM</i>	Vector dot product minimisation

Greek Symbols

α	Absorptivity, Thermal diffusivity (m ² /s)
β	Coefficient of thermal expansion (1/K)
ΔT	Temperature difference (K)
δ	Distance (m)
η	Efficiency
γ	Power factor, Phong exponent
κ	The spectral absorption coefficient
λ	Wavelength (μ m)

μ	Viscosity (Pa · s)
ϕ	Angle
ρ	Reflectivity, Density (kg/m ³)
σ	Stefan-Boltzmann constant 5.67×10^{-8} (W/m ² K ⁴)
σ_w	The Wien's constant 2897 (μm.K)
τ	Transmissivity
θ	Angle
ν	Kinematic viscosity (m ² /s)
ε	Emissivity
ξ	Light recycling factor
F	View factor

Subscripts

∞	Ambient
B	Base
C	Convex
eff	Effective
fil	Filament
g	Gas
i	Incident
q	Quartz
R	Ray
R	Reflector
r	Reflected

<i>rad</i>	Radiation
<i>s</i>	Surface
<i>skew</i>	Skewness
<i>sub</i>	Subdivision
<i>t</i>	Transmitted
<i>tung</i>	Tungsten

Chapter 1

Introduction

For millennia humans have manipulated sources of heat to their advantage. The discovery of fire was a defining moment which allowed the energy stored in wood to be converted into heat. This greatly enhanced the lives of prehistoric humans by providing a controllable energy source that could afford warmth in harsh weather, deter predators, and for the first time, allow the cooking of food. Today we still manipulate heat sources to our benefit for many of the same reasons as prehistoric humans, although the methods used to do so are very different.

The burning of fuels was heavily relied upon as a light source up until the early 20th century before dependable and long-lasting incandescent sources were established. Incandescence is achieved through the heating of a resistive filament to a high temperature by the flow of electrical current (i.e. Joule heating) and offers smaller, brighter, and more reliable light sources in comparison to its predecessors. An example of a contemporary incandescent light source is depicted in Fig. 1.1 showing the important components including the filament, transparent envelope, and fill gas.

Despite the advantages that incandescent sources bring, they are highly ineffective when used for lighting purposes, with typical luminous efficiencies of less than 5% [1]. The incandescent lamps were soon repurposed as heat sources due to the intense infrared (IR) radiation emitted when the filament is heated to high temperatures. The low luminous efficiency of the incandescent lamps was no longer a concern when utilised for this purpose since the radiation emitted outside of the visible wavelength range is still useful for heating despite not being detectable by the human eye.

In the past century, many new industrial processes have arisen such as thermoforming

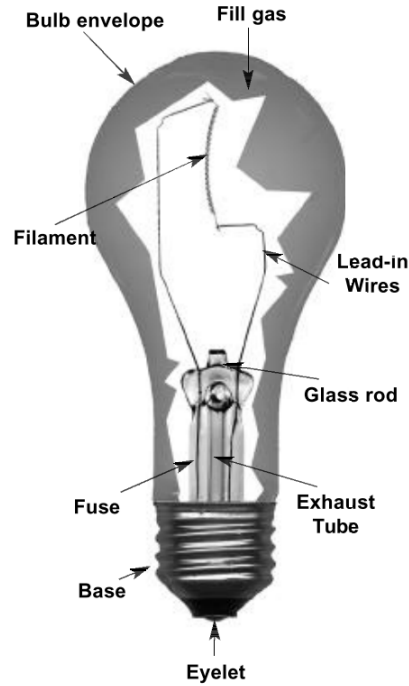


Figure 1.1: Example of an incandescent light source. Reproduced from [2], with the permission of the American Association of Physics Teachers.

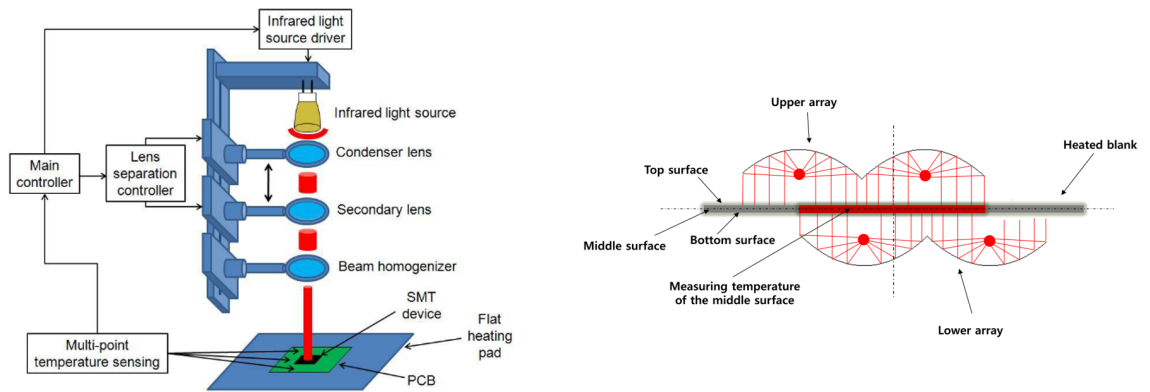
(the heating of polymer materials before being shaped by a tool), the curing of polymers, the processing of paper and the drying of food [3–5]. IR heating is a key technology in the aforementioned applications and many others such as the heat treatment of metals, soldering, and brazing as well as the testing of high-temperature components which requires very high intensities. The purpose of an IR heater is to transfer radiant energy to a surface thereby increasing the temperature of the target. IR heating is distinguished by its short response times with little to no preheating, the ability to heat in the absence of convection or conduction (i.e. without a means of physical contact with the target), the efficient use of energy through direct heating of the target (and not the surrounding air/medium), and the potential to reflect, focus or diffuse the radiation to suit the requirements of the application. In many cases, IR heating strategies are more cost-effective to acquire and operate than convection or conduction based alternatives [6, 7].

The solid state additive manufacturing process of “cold spray” is another example of an application which can be improved by strategically using a heat source. During this process, metal powders are accelerated to supersonic speeds before impacting upon a substrate [8]. The kinetic energy of the particles upon impact causes plastic deformation of both the particle

and substrate, allowing a metallurgical and mechanical bond to be formed. High-intensity heat can be used either prior to particle impact to soften the target substrate, similar to the process of supersonic laser deposition [9], or post impact to improve mechanical properties of the coating through an in-process heat treatment [10]. This is a pertinent example as the need for a low cost, small, and high power density heat source for this process initially led to the current research. Thus cold spray will be a common application example throughout this text.

The high-intensity radiation necessary for use with cold spray and other high temperature processes is acquired primarily using laser sources, arc lamps, or IR radiation emitted from an incandescent source. Both lasers and arc lamps can achieve higher heat fluxes than focused IR heating but with greater safety concerns and at a higher cost. As a result, IR heating is generally considered a safer and cheaper alternative for low to medium level intensity radiation applications (i.e. $< 300\text{-}400\text{ W/cm}^2$).

Two examples of IR heating technology are presented in Fig. 1.2, with Fig. 1.2a showing a device developed for rapid soldering applications and Fig. 1.2b showing a device which is used to preheat steel before a forming process. The former device allows the bulk soldering of small components in a more controlled and flexible manner than traditional soldering approaches allow. The benefit of the latter device was to decrease the processing time and increase the efficacy of a steel forming process. Other applications of focused IR heating will be explored in detail in the literature review in Chapter 2.



(a) Soldering device constructed using reflectors and lenses [11]. (b) Multiple overlapping heaters employed for metal forming [12].

Figure 1.2: Examples of IR heating technology.

In the case of metals, the heat should be targeted only over a small area of the component

in order to prevent prolonged localised heating, which can produce adverse changes in the microstructure. Incandescent heat sources can meet these requirements by employing a reflector to concentrate the emitted radiation through a small outlet area. This type of device is typically referred to as a focused IR heater (FIRH). The FIRHs presented in the literature or through commercial avenues use simple elliptical shapes which are designed under the supposition of a point emission source. Since the solid tungsten filament of the incandescent source inherently must have a nonzero size (also known as an “extent”), the standard reflector designs are not ideal and in many cases deliver efficiencies and heat fluxes well below the theoretical maximum.

Table 1.1 lists a selection of the commercially available FIRHs. For context, the theoretical maximum heat flux that can be emitted from a tungsten filament at 3000 K is ~ 460 W/cm². This sets an upper bound on the heat flux achievable on the target surface [13]. Each of these devices uses an elliptical reflector to focus the radiation onto a small spot. As shown, the efficiencies of the devices are poor, with both the SpotIR and Spot S1000 transferring less than 5% of the total power input to the target. Similarly, for the heat flux output, the listed values are well below the theoretical maximum. The Precision Controls Systems (PCS) SpotIR delivers the lowest efficiencies but with heat flux outputs that are suitable for applications other than soldering. The Optron unit provides higher efficiency than the other devices listed; however, this is accompanied by low power output, which limits the range of applications where this device is useful. The Lightbeam spot S1000 delivers both a low heat flux output and low power output. The most useful device for a range of applications appears to be the Thermo Riko GL398, which produces the highest power and heat flux output of the devices shown.

Table 1.1: A brief summary of the commercially available FIRHs [14].

Manufacturer	Device	Power input (W)	Power output (W)	Diameter (mm)	Heat flux output (W/cm ²)	Efficiency
PCS	SpotIR 4085	750	32	6.35	101	4.3%
Thermo Riko	GL398	3000	350	20	111	12.0%
Lightbeam	Spot S1000	1000	43	20	14	4.3%
Optron	600.5100	150	24	6	85	16.0%

The low efficiencies and heat fluxes are a function of the nonsymmetric extent of the filament, which for IR sources typically take the form of a cylindrically shaped emitter.

The extent of the source may be partially compensated for by increasing the size of the parabolic and elliptical reflector to reduce the relative size of the filament emitter. However, this is of limited benefit due to the difficulty in accommodating a sizeable reflector as either stationary or a mobile heat source. This is coupled with the additional cost and time required to manufacture and finish a reflector of a large size.

The design of FIRH reflectors is typically performed using manual “trial-and-error” based techniques, which are both time-consuming and unlikely to find a true optimum. It is for these reasons that commercially available FIRHs exhibit poor efficiencies, low heat flux outputs and are consequently unsuitable for many applications currently catered for by lasers and arc lamps. Presently, focused IR technology is limited to low powered applications where a large reflector can be deployed. If higher efficiencies and power densities can be achieved from these devices with a smaller reflector footprint, a more extensive range of applications will become suitable for this heating approach, potentially allowing the displacement of competing technologies.

The efficient transfer of light from a source to a target is a challenging problem which falls under the remit of illumination design. In this field, standard reflectors are no longer used but instead shapes optimised for a particular source geometry. There are many examples of this, including street lighting luminaires, car headlights, and projectors for which a bespoke reflector shape is tailored to a given source geometry. A manual tailoring approach was widely used in the field of illumination design, but more recently automated optimisation routines have come to the fore. Automated optimisation routines address the drawbacks of the manual trial-and-error based approach by negating the need for an experienced designer, reducing the design time and generally delivering higher performing solutions in comparison. Despite the benefits of using these routines, they have not yet been applied to FIRHs, and thus, there is substantial benefit to be gained from doing so.

At present, there is a lack of research regarding the design of focused IR technology. This work aims to address this by investigating the thermal performance of an IR source and developing an automated design strategy for FIRHs. This will allow for the manufacture of devices which are capable of delivering higher efficiencies and heat flux outputs when compared to the commercially available FIRHs. These improvements will permit focused IR technology to be employed in a broader range of “high radiation intensity” applications (e.g. cold spray), which are currently catered for by rival technologies such as lasers and arc lamps. Furthermore, a secondary aim of this work is to develop a more compact FIRH that

is significantly smaller than the devices currently available on the market, which will further increase the usability of the focused IR technology for cold spray and the other potential applications discussed.

1.1 Thesis outline

A summary of the thesis layout is discussed in this section and presented in Fig. 1.3.

Chapter 2 – Literature review

This chapter presents an investigation into the literature of the concepts surrounding the design and modelling of a FIRH. Firstly, an introduction to heat transfer is presented with a particular focus paid to radiative heat transfer. The quartz tungsten halogen (QTH) lamp is introduced before the lack of research dedicated to the thermal performance of these sources is highlighted. An overview of the techniques used to focus IR radiation is explored, including discussion on the advantages and drawbacks of each. After which, a detailed outline of the commercially available FIRHs is provided, and their performance discussed.

The literature review then moves on to the design of FIRHs. A focus is drawn to illumination design, nonimaging optics (NIO), and the design of radiation enclosures, which provides insight into the design approaches appropriate for the development of a custom FIRH reflector. Techniques for the modelling of radiative heat transfer and shape optimisation are reviewed, and a conclusion is presented regarding the most suitable methods for use in this work.

Chapter 3 – Energy Efficiency of a Quartz Tungsten Halogen Lamp

This chapter describes the approach used to characterise the high-temperature IR source employed in this work concerning radiative power output (i.e. electrical–radiative efficiency), heat flux output, and the effect of filament temperature on these performance characteristics. New and modified techniques are described, which allow the study of these compact sources accurately and at a lower cost and complexity than has been described previously in the literature. A numerical model is developed, which allows a deeper understanding of the physics driving the performance of the lamp.

Chapter 4 – Benchmarking of FIRH performance and limits

This chapter discusses the results of a characterisation of a commercial FIRH. The theoretical limits on the performance of the FIRH are outlined and compared to that of the performance of commercially available FIRHs.

Chapter 5 – Development of a 2D Monte Carlo ray tracing based optimisation routine

The development of an accurate model which takes into account the physics underlying a FIRH is a sizable challenge. Therefore, a 2D Monte Carlo ray tracing (MCRT) prototype model is first developed in this chapter to validate the modelling and optimisation technique, while accepting a compromise in the accuracy of the model output. The main components and assumptions of the model are outlined, as well as the algorithms and techniques used to design custom reflector shapes.

Chapter 6 – FIRH design and characterisation

In Chapter 6, the 2D model is applied to the optimisation of a FIRH. The manufacturing strategy employed to fabricate the device and the design considerations are discussed. Comprehensive testing of the performance of the device is detailed, including the radiative power output, filament temperature during operation, and the startup time of the reflector. Recommendations for improvements to the manufacturing and finishing of the reflectors are also provided.

Chapter 7 – Development of a 3D Monte Carlo ray tracing optimisation routine

A 3D MCRT model is developed which requires fewer assumptions than the 2D model described in Chapter 5. The main steps required for the rigorous modelling of the 3D shape are provided including a new algorithm for the ray tracing of axisymmetric shapes, which is significantly faster and more accurate than the alternative methods tested from the literature. This chapter concludes with the validation of the model versus experimental measurements, showing acceptable agreement.

Chapter 8 – Design and optimisation of 3D FIRHs

The details of the design of various FIRHs using the 3D MCRT model are provided in this chapter. This includes a range of reflectors optimised for IR sources that are adopted by commercially available devices, as well as étendue and skewness-optimised devices. The effect of light recycling on the performance of the FIRHs and the practical implications of this effect is discussed. Design strategies for FIRHs with specific performance requirements are detailed. In particular, approaches for selecting the outlet of the FIRH to maximise heat flux, efficiency or both metrics simultaneously are discussed. Several metrics which allow comparison of reflectors of differing sources and outlet sizes are also developed.

Chapter 9 – Conclusions and future work

Finally, this chapter concludes the main aspects of this work and outlines future directions for follow on research.

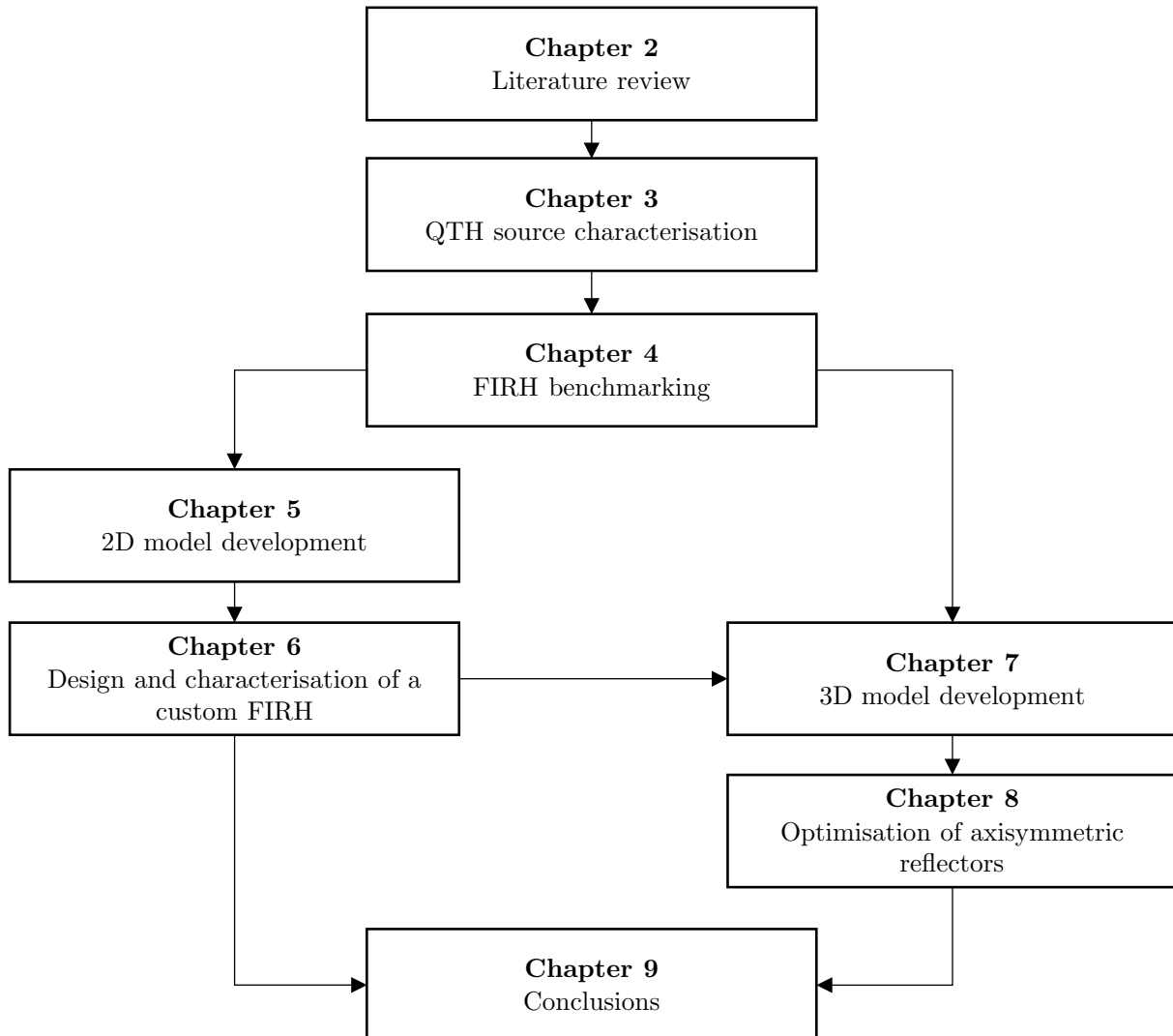


Figure 1.3: Flowchart of the thesis.

Chapter 2

Literature review

2.1 Introduction

This chapter aims to inform the reader of the relevant literature regarding IR heating technology, the physics underlying the operation of these devices, and the design methodologies employed in related fields of research. Areas which warrant further study and give rise to the primary area of investigation for this work will be highlighted throughout this chapter. Firstly the modes of heat transfer will be introduced as these govern the operation of IR heating technology. This leads to a discussion of the sources employed in this field and familiarisation with commercial FIRHs. Finally, the shortcomings of these devices will be highlighted before exploring alternative design approaches from the fields of illumination design, solar concentration, and radiation enclosures. The chapter concludes by summarising the main findings from the literature and proposing a research direction for this work.

2.2 Heat transfer

Heat transfer is the transportation of energy from one location to another due to a temperature differential. Since the purpose of an IR heating device is to transfer heat from a source to a target surface, the study of heat transfer is fundamental to the understanding of its operation. There are three mechanisms by which heat can be transferred: conduction, convection, and radiation. Both convection and conduction require a medium of transport such as a solid or fluid. Conversely, radiation heat transfer can occur without the need for a transport medium. The three mechanisms are illustrated in Fig. 2.1.

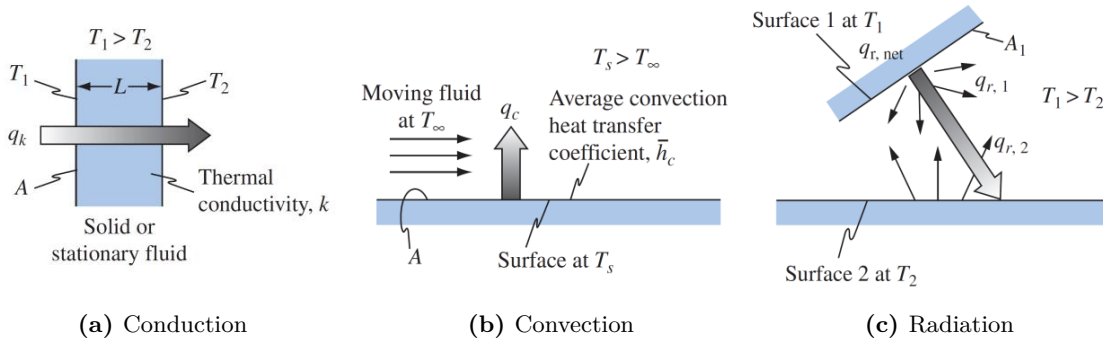


Figure 2.1: Illustration of the modes of heat transfer [15].

The transfer of heat from one location to another is governed by the laws of thermodynamics [16, 17]. The first and second law aid the understanding of the limits of heat transfer processes and are particularly pertinent to this work. The first law of thermodynamics, also known as the law of conservation of energy, states [18]:

Energy can neither be created nor destroyed. It can only change from one form to another.

This implies that the total energy in a closed system can only change if energy passes through the boundary of the system. The most forthright application of this law is to state that the total electrical input provided to an IR heating device is equivalent to the heat dissipated by that device when operating in steady-state conditions. This assumes that no work is being performed by the system and steady state operation.

The second law of thermodynamics asserts that energy has *quality* as well as quantity and that a process has a *direction* [18]. The first law is only concerned with the quantity of energy in a process or system, whereas the second law, in essence, is concerned with the reversibility of the process. The second law is often expressed in the form of the Clausius statement:

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

It can be concluded from this statement that work must be performed to transfer heat up a thermal gradient from cold to hot. Hence for a passive system, heat can only flow down a gradient from hot to cold, and never in the opposite direction. Since an infrared heating device is passive, heat must always flow from the source to the sink, and consequently, the sink can never reach a higher temperature than the source. A further implication of this law is that the heat flux output at the outlet of the FIRH cannot exceed the heat flux output of the surface of the source. This is often referred to as the brightness theorem [19]. This concept was discussed in detail regarding solar applications and nonimaging optics by *Winston et al.* [13] in the early work titled “Nonimaging optics” and a more recent publication regarding solar concentrators [20]. This limitation will be expanded upon later in this work.

Since radiation is the primary energy transport mechanism of an IR based heating device, the following section will focus on the fundamentals of radiative heat transfer. Convection and conduction will first be briefly described as these play an important but less significant role.

2.2.1 Conduction

Conduction is the transfer of energy from high energy particles to low energy particles in a solid, liquid, or gas due to physical interactions. For fluids, these interactions take the form of random collisions of the molecules, which pass kinetic energy from one molecule to another. This inevitably disperses energy from areas of high concentration to low concentration. Within a solid, energy is transferred through vibrational interactions of the molecules of the material. Conduction is the primary mechanism by which heat can be transferred through an opaque solid.

Fourier’s law readily describes heat transfer by conduction, which for an assumed 1D flow is as follows:

$$\dot{Q}_{cond} = -kA \frac{T_2 - T_1}{x_2 - x_1} = -kA \frac{dT}{dx} \text{ (W)} \quad (2.1)$$

The temperature gradient $\frac{dT}{dx}$ incorporates both the temperature differential and the distance over which conduction is taking place. The negative sign ensures that a positive quantity represents a positive flow in the x-direction.

2.2.2 Convection

Convection is typically regarded as the most complicated heat transfer mechanism due to the need to account for thermal gradients as well as velocity gradients. For radiation and conduction, the media exchanging heat can be considered static, whereas convection relies on the movement of fluids for bulk transport to take place. Convection can be classified as either natural or forced. With natural convection, the bulk fluid motion is caused by buoyancy effects due to the varying density of the fluid at different temperatures. The rate of heat transfer is increased with forced convection, which occurs when a pump or fan drives movement of the fluid over a surface. Newton's law of cooling describes the rate of heat transfer via convection for a heated surface:

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad (2.2)$$

Here, h is the heat transfer coefficient, which is dependent on several factors such as the fluid and surface properties, the geometric properties of the system and the flow conditions (i.e. laminar or turbulent). A_s is the surface area and T_s and T_∞ are the surface and the ambient temperature respectively.

2.2.3 Radiation

Radiation is the emission of internal energy from a material and occurs at all temperatures above absolute zero [16], i.e. when the atoms and molecules in a body have kinetic energy. The photons emitted from the surface transfer energy away from the material, resulting in a reduction in temperature. The energy carried by a photon is a function of its wavelength with shorter wavelengths having more energy than longer wavelengths. Radiation is a volumetric phenomenon, although it is often considered a surface phenomenon since for an opaque material, the internal radiation will be absorbed by neighbouring atoms and fail to reach the surface. Thus, only the radiation emitted close to the surface will reach the ambient. This assumption is not valid for "semitransparent" materials, which will attenuate some of the radiation passing through the material.

Radiation can be emitted across the entire electromagnetic wavelength spectrum: on one end high energy gamma radiation and on the other low energy microwave radiation. The electromagnetic spectrum of wavelengths is illustrated in Fig. 2.2. Thermal or IR radiation is emitted due to the energy transitions of molecules, atoms, and electrons of a material,

throughout wavelengths ranging from approximately $0.1 \mu\text{m}$ to $100 \mu\text{m}$ [16]. Thermal radiation will typically be the dominant mode of heat transfer in a vacuum, a low-pressure environment, or when temperatures are high.

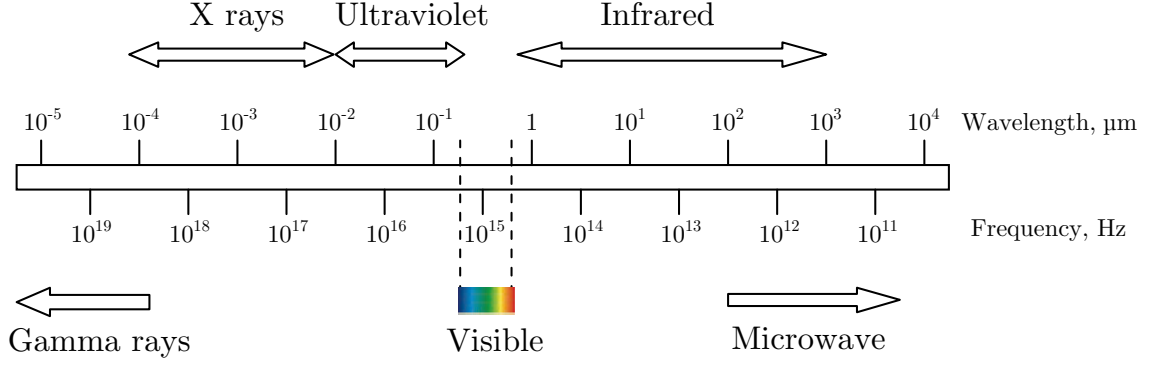


Figure 2.2: The electromagnetic spectrum [21].

The definition of IR radiation can be further classified into three subcategories of **NIR** - **near infrared** (0.75 - $1.4 \mu\text{m}$); **MIR** - **medium infrared** (1.4 - $3 \mu\text{m}$); and **FIR** - **far infrared** (3 - $1000 \mu\text{m}$) [7]. Radiation in the FIR band is characterised by longer wavelengths, which carry comparatively less energy and are absorbed well by water and biological materials [21]. High-temperature IR sources radiate at a surface temperature of up to $\sim 3000 \text{ K}$ in the wavelengths of $\sim 1 \mu\text{m}$ and therefore, are categorised as a NIR or shortwave sources.

2.2.3.1 Blackbody radiation

A blackbody emits the maximum amount of radiation possible at all wavelengths and all temperatures; it serves as a standard to which radiation from a real surface can be compared due to its ideal character. Blackbodies also absorb all incident radiation across all wavelengths and directions. The absorbed radiation is converted to thermal energy (i.e. particle motion at the atomic level), which may be later re-emitted.

The emission of radiation from a blackbody is described by the Stefan-Boltzmann law and Planck's law, which can be used to estimate the total emissive power and spectral emissive power distribution respectively. The Stefan-Boltzmann law states that the radiant intensity emitted from a blackbody surface is proportional to the fourth power of its absolute temperature:

$$E_b = \sigma T^4 \quad (2.3)$$

Here, σ is the Stefan-Boltzmann constant and T is the surface temperature in degrees Kelvin.

It is noteworthy that radiative emission is a function of the 4th power of the temperature, whereas conduction and convection are functions of the first power, i.e. they are linearly proportional (when disregarding the effect of material properties varying with temperature). This indicates that radiation will play a more significant role than conduction or convection when there is a high temperature difference between two media.

Radiation emitted from a surface is said to be diffuse, meaning that it is independent of direction. However, if measured over a range of angles, a radiant intensity which is proportional to the cosine of the angle of emission (to the surface normal) would be observed. The reason for this discrepancy is that as the angle to the normal is increased, the projected area of the emitting surface is reduced. This is referred to as Lambert's cosine law [16]:

$$E_{\lambda b} = i_{\lambda b} \cos(\theta) \quad (2.4)$$

Where $E_{\lambda b}$ is the measured emissive power (W/m^2) at an angle of θ to the normal and $i_{\lambda b}$ is the radiant intensity emitted from the surface. An example of a uniform and a Lambertian distribution is shown in Fig. 2.3.

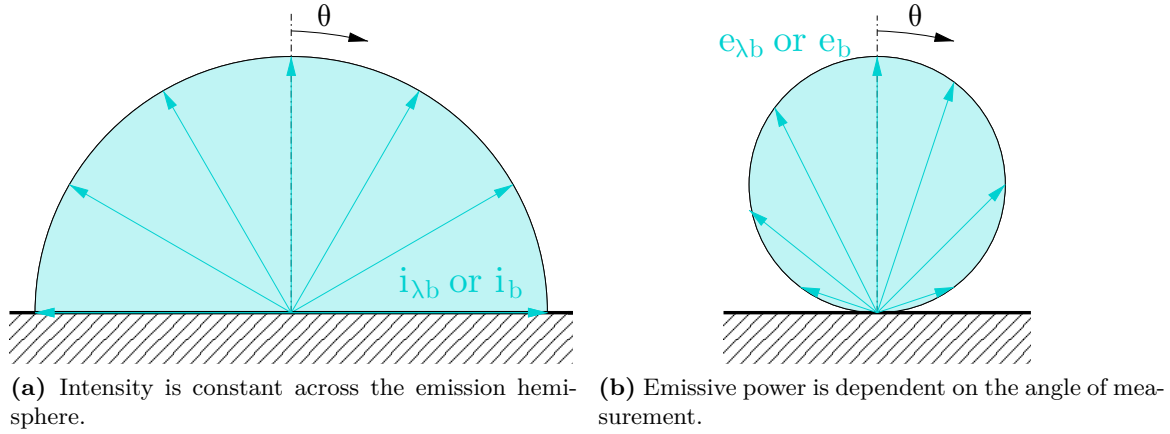


Figure 2.3: Comparison between intensity and emissive power emitted from a surface [22].

Real surfaces do not emit and absorb at the same rate as a blackbody. Emissivity is a measure of the efficiency at which a surface emits thermal radiation and is defined as the ratio of the radiation emitted from a surface when compared to a blackbody at the same temperature. The total hemispherical emissivity is as follows [16]:

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} \quad (2.5)$$

For a blackbody, the emissivity is by definition unity. Emissivity can be analysed on a wavelength basis (referred to as the spectral emissivity) and can vary strongly with both temperature and wavelength. Emissivity can either be determined as normal to the surface, be provided as a function of an angle to the normal, or be integrated over the emission hemisphere (hemispherical emissivity). However, the difference between these values is often not considered for most practical examples. Greybody radiation is similar to blackbody radiation in that the emissivity of a grey body is independent of wavelength, but is always less than that of a blackbody. The greybody assumption is often pragmatic when the change in emissivity with wavelength is not significant such as when the primary absorption and emission wavelengths are similar, or a material has a relatively flat emissivity profile over the range of wavelengths of interest (e.g. many metals in the IR radiation band).

Eq. 2.3 can be expanded to include emissivity and surface area, which predicts the total emissive power of a real surface:

$$E(T) = \varepsilon \cdot \sigma \cdot A \cdot T_s^4 \quad (2.6)$$

Where A is the area of the heated surface, and T_s is the surface temperature. For radiative heat exchange between two bodies at different temperatures, this equation can be expanded to the following:

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot A \cdot (T_2^4 - T_1^4) \quad (2.7)$$

Eq. 2.7 assumes a *small convex body within a large enclosure* which implies that the surface area of surface 1 is considerably smaller than the surface area of surface 2 and that surface 1 cannot radiate heat to its own surface by the fact that it is convex. Despite this assumption appearing quite limiting, this equation applies to many practical radiation dominant engineering problems.

While the Stefan-Boltzmann equation describes total emissive power, Planck's law describes the spectral emission intensity of a surface at a given temperature:

$$E_{b,\lambda}(\lambda, T) = \frac{2\pi hc_0^2}{\lambda^5} \frac{1}{e^{\frac{hc_0}{\lambda k_b T}} - 1} \quad (2.8)$$

Here, λ is the wavelength, k_b is the Boltzmann constant (not to be confused with the Stefan-Boltzmann constant from Eq. 2.3), h is Planck constant, and c_0 is the speed of light in a vacuum. This equation can be used to calculate the spectral power emitted over a range of wavelengths. Integration of this equation over the entire electromagnetic wavelength spectrum

results in the Stefan-Boltzmann law presented in Eq. 2.3.

As discussed previously, temperature plays a significant role in the wavelength distribution emitted from a heated surface. As the temperature of a surface rises, the emitted intensity significantly increases (due to the 4th power relationship), and the wavelength distribution is shifted towards shorter wavelengths, as is illustrated in Fig. 2.4.

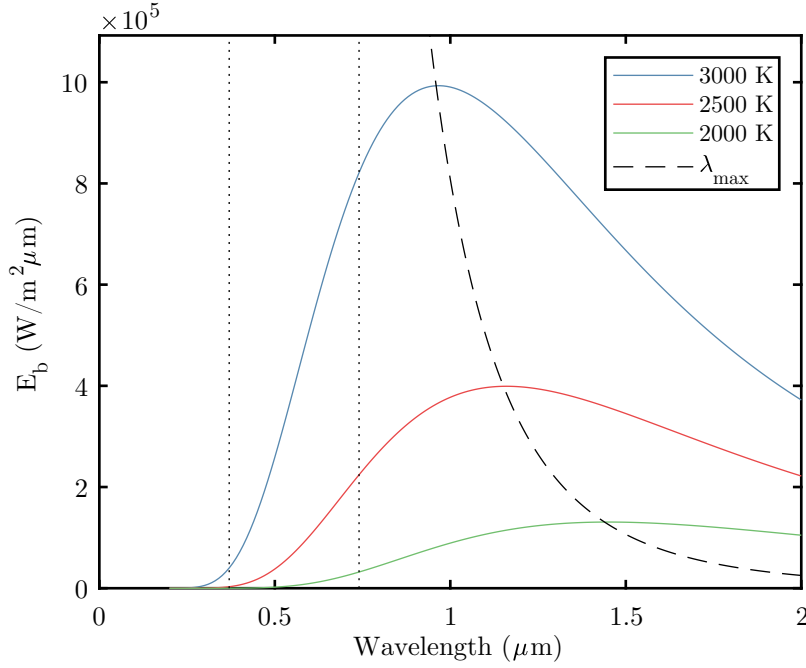


Figure 2.4: Blackbody spectral distribution at various emission temperatures. The dotted lines indicate the visible light band. Adapted from [22].

For each of the temperatures shown, Wien's displacement law can be used to determine the wavelength at which peak emission occurs:

$$\lambda_{max} = \frac{\sigma_w}{T} \quad (2.9)$$

Where σ_w is Wien's constant of 2897 $\mu\text{m.K}$ and T is the temperature of the emissive surface in degrees Kelvin.

2.2.3.2 Absorptivity, reflectivity, and transmissivity

As illustrated in Fig. 2.5, there are three potential outcomes for radiation incident on a surface:

1. The radiative energy is absorbed through conversion into thermal energy by physical interactions with the material at the atomic scale.

2. The incident radiation is reflected.
3. The radiation is transmitted through the transparent body.

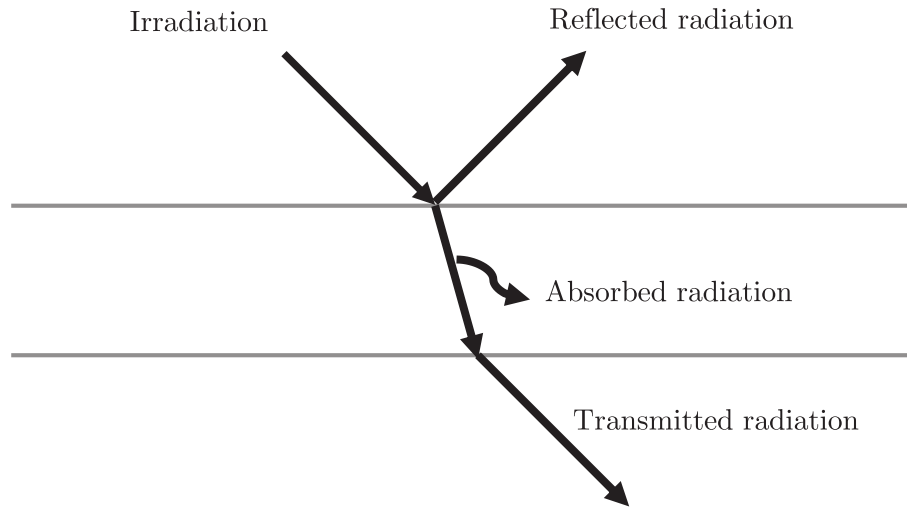


Figure 2.5: Absorption, reflection, and transmission of incident radiation. Adapted from [21].

Surfaces may be described as reflective or absorbent, and bodies may be described as transmissive or opaque. Bodies which allow the transmission but also attenuate radiation are referred to as semitransparent. All materials which allow the transmission of radiation are semitransparent, but in cases such as with air, the attenuation is so small that it is considered negligible for nearly all practical cases.

Several mechanisms can lead to the absorption of thermal radiation. The mechanism which plays the most dominant role depends on the wavelength of the incident radiation [6]:

1. Changes in electronic state, which occurs between the wavelength range of 0.2 to 0.7 μm .
2. Changes in vibrational state, which occurs between 2.5 to 1000 μm .
3. Changes in rotational state, which correspond to wavelengths of above 1000 μm .

The potential of a photon with a given wavelength to modify the state of the electrons or atoms determines how a material will interact with that photon. If the material is not susceptible to being excited by radiation at a given wavelength, the photon will either be transmitted or reflected.

Reflections can be defined as either diffuse or specular, as illustrated in Fig.2.6a and b. A diffuse surface is one for which a reflected ray is said to be directionally independent,

irrespective of the incident angle. Conversely, specular reflection occurs when a surface is smooth, and the reflection angle is equal to the incident angle. For most real surfaces, a combination of diffuse and specular reflection will occur, as shown in Fig. 2.6c, which depicts a specular peak protruding from a diffuse reflection hemisphere.

The ratio of diffuse to specular is a function of the smoothness of the surface and the relative size of the roughness compared to the radiation wavelength. Longer wavelengths are less susceptible to scattering from surface defects, while shorter wavelengths are more easily scattered. *Ulably et al.* [23] suggests the following equation for determining the reflection regime of incident radiation:

$$Ra_{spec} < \frac{\lambda}{(32 \times \cos\theta)} \quad (2.10)$$

where λ and θ are the wavelength of the radiation and incident angle respectively. If Ra_{spec} is less than the right hand side of the equation, the reflection regime can be considered to be specular.

A practical example of this phenomenon is Rayleigh scattering which gives rise to the blue sky through the scattering of shorter blue wavelengths by atoms in the upper atmosphere. Therefore, smoothness must be defined relative to the wavelength of the radiation and not an absolute value — a surface is smooth if the height of the surface roughness is substantially less than the size of the wavelength of the radiation impinging upon that surface. When analysing radiative heat transfer using analytical methods, it is often assumed that reflections are diffuse due to the difficulty in handling specular reflections.

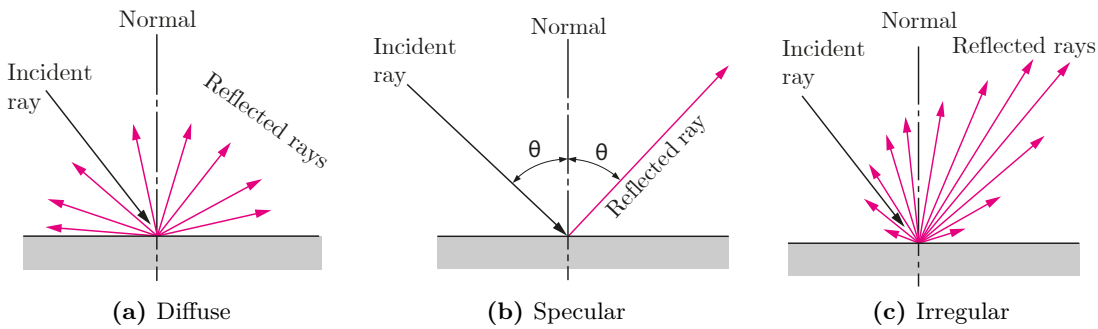


Figure 2.6: Diffuse and specular reflection regimes [16].

2.2.3.3 Kirchhoff's law

The total fraction of radiation incident on the surface, G , must equal to the sum of the absorbed, reflected or transmitted radiation as per the law of conservation of energy [16]:

$$G = G_{absorbed} + G_{reflected} + G_{transmitted} \quad (2.11)$$

Dividing the above equation by the incident radiation:

$$1 = \alpha + \rho + \tau \quad (2.12)$$

For an opaque material where transmissivity can be neglected ($\tau = 0$):

$$1 = \alpha + \rho \quad (2.13)$$

Therefore, incident radiation must either be absorbed or reflected. Additionally, the absorptivity and emissivity can be equated using Kirchhoff's law of thermal radiation, which states that at a given wavelength and emission angle, the thermal radiation entering and leaving a surface must be equal:

$$\varepsilon_{\lambda,\theta}(T) = \alpha_{\lambda,\theta}(T) \quad (2.14)$$

This law can be derived based on the energy balance of a body under thermal equilibrium with its surroundings. Siegel and Howell provided a rigorous derivation for the general form of Kirchhoff's law as well as the more restricted variants [24]. Using this relation and Eq. 2.13 it can also be inferred that the reflectivity of an opaque surface is:

$$\rho = 1 - \varepsilon \quad (2.15)$$

Hence, the reflectivity, emissivity, and absorptivity can be determined with only knowledge of one value when considering opaque materials. However, this assumes a small temperature difference between the source and the surface of the body in question. Therefore, this does not apply to all radiation problems and therefore this assumption must be applied selectively.

2.2.3.4 Radiosity

As discussed in section 2.2.3.2, radiation incident on an opaque surface can result in either reflection or absorption. The reflected radiation on the surface will then be added the emitted radiation from that surface. The total outgoing radiation from a surface due to the contribution of reflection and emission is referred to as the radiosity:

$$J = E + G_{reflect} \quad (2.16)$$

For a blackbody, J will always equal to the emitted radiation since all incident radiation will be absorbed; however, for a real surface, reflected radiation will increase the apparent brightness of the surface by combining with the emitted radiation. The incident radiation may be from a separate surface or from that same body if it is concave.

2.2.3.5 View factor based analysis

When analysing a radiative heat transfer problem with multiple surfaces which are separated by a nonparticipating medium, a view factor based analysis is the most rudimentary way to determine the rate of radiative heat transfer. View factor based analysis is classed as an analytical method, which provides an exact solution for a given problem formulation.

A view factor is a geometrical property of radiative heat transfer problems that is independent of surface properties and temperature. View factors embody how likely radiation emitted from one surface is to intercept another surface. This is illustrated in Fig. 2.7, which shows the view factors for a small body with a surface area of A_1 enclosed within a larger surface with an area of A_2 . These surfaces will be referred to as S_1 and S_2 from herein. View factors are described with the capital letter F with subscripts that denote the surfaces to which the view factor is concerned. For example, F_{12} denotes the radiation that is emitted from S_1 and intercepts S_2 . As previously mentioned, a small convex object within a large cavity is a common assumption applied to radiative heat transfer problems, which is a simplification of the view factors. This assumption results in the view factors reducing to:

$$F_{12} = 1; F_{11} = 0; \quad (2.17)$$

$$F_{21} = \frac{A_1}{A_2} \cong 0; F_{22} = 1 - \frac{A_1}{A_2} \cong 1 \quad (2.18)$$

Since S_1 is convex, no radiation emitted from the surface can re-intercept the surface, and

since S_2 encloses S_1 , all of the radiation emitted will intercept surface S_2 . On the other hand, the likelihood of radiation intercepting S_1 from S_2 is low due to the area difference. Hence, the heat transfer from the cavity wall to the small object can be ignored during the analysis of the system without compromising the accuracy of the solution. Further discussion of view factors as well as view factor expressions for common radiation problems can be found in the work of *Cengel et al.* or *Incropera et al.* [16, 17].

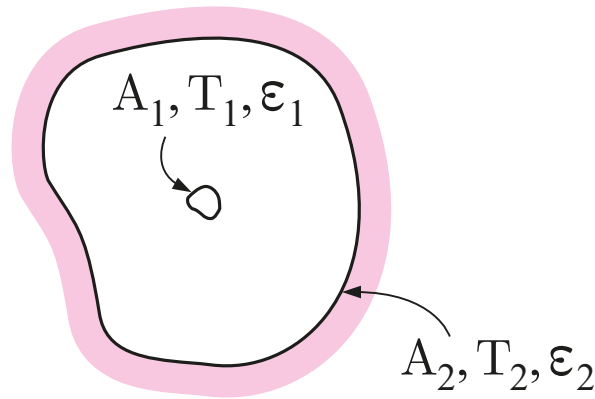


Figure 2.7: A small convex object within a large cavity [16].

View factors can be determined by the summation rule (where the view factors must all add to 1), the reciprocity relation, or superposition using known geometries and view factors [16]. Determining view factors for complicated geometries can be quite involved, although, in some cases, the complex surfaces can be replaced with several simpler ones which are more manageable. Alternatively, the Hottel's crossed-string method can be applied to a problem, which allows the enumeration of view factors using measurable distances and simple formulaic relationships.

Although a view factor based analysis allows accurate solutions to be determined for a given problem, it is limited to trivial geometries with a small number of surfaces. Analysis of an enclosure which consists of N surfaces requires evaluation of N^2 view factors and, therefore, the complexity of a problem grows quadratically with the number of surfaces. Analysing partially specular and diffuse surfaces is also problematic using this approach. Modest [25] recommends statistical methods such as ray tracing (RT) for the calculation of partially specular surfaces which are more complicated than a sphere or cylinder.

2.3 QTH source

This section will briefly discuss the development of incandescent sources and the relevant characteristics and properties of high powered IR lamps.

2.3.1 IR source technology

The most common source for high-intensity IR heating technology is the QTH lamp. This lamp employs a high-temperature tungsten filament surrounded by a quartz envelope and a halogen-doped inert fill gas. The development of this technology arose in numerous steps spanning almost two centuries starting from the 1760s. The first case of incandescence was documented by Ebenezer Kinnersley in 1761 [26] while researching the effect of power transmission through a brass wire. Kinnersley did not fully understand the significance of this discovery as the research focused on wire drawing of the softened metal as opposed to higher impact lighting applications. It was not until almost 80 years later when a Belgian scientist, Marcellin Jobard, electrically heated a carbon filament in a vacuum and in doing so, created the first incandescent light bulb [27]. Over the following decades, Thomas Edison played an integral role in the commercialisation of this technology, bringing bright and clean light sources to the masses [28]. Carbon-based filaments have significant drawbacks with regard to their thermal and mechanical properties as this material is very brittle and evaporates rapidly at high temperatures. As a result, metal filaments with lower rates of evaporation became prevalent soon after the initial breakthrough.

The first tungsten filament was developed in 1904 [29], and many years later, an inert gas at high pressure was added to reduce the rate of evaporation at high temperature. It was not until 1959 that halogen lamps were introduced, which allowed higher operating temperatures and longer lamp lifetimes due to the ability of the halogen gas to return evaporated tungsten to the filament [28]. The use of halogen dopants within the fill gas eventually led to the development of the modern QTH lamps used today, examples of which are shown in Fig. 2.8. There have been several minor improvements since the 1960s such as the sealing technique [30], manufacturing of the filament for greater mechanical stability [31], startup current limiting devices which increase lamp lifespan [32], and geometry improvements to the filament [28].

The vast majority of the energy emitted from a high-temperature filament in a QTH lamp is wasted when employed for lighting purposes. Less than 5% of the radiation emitted from

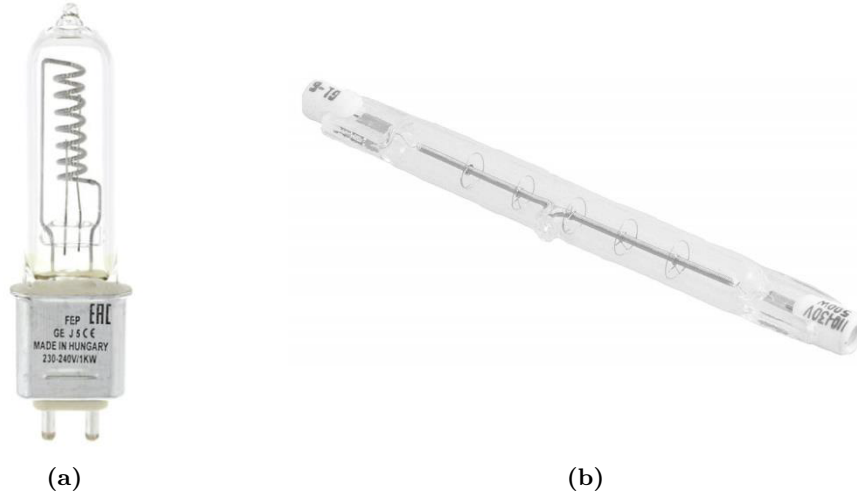


Figure 2.8: QTH lamp examples: (a) 1000 W single-ended lamp, (b) 500 W double-ended lamp.

a filament emitting at 3000 K is within the visible range (390-700 nm) according to the work of *Ognjen et al.* [1]. However, this energy is not lost when used with IR heating applications, which can utilise the entire visible and IR spectrum if the wavelength-dependent absorptivity of the material permits. This has led to the widespread use of QTH lamps outside of the primary base of lighting applications with polymer and food processing [3, 6], curing [33], domestic heating [5], soldering [11] and research [34] being common applications.

The key characteristic which distinguishes QTH lamps from other sources is the high temperature of the filament. For example, longwave IR heaters such as those found in bars, restaurants, and other social gatherings, operate at much lower temperatures. This limits the maximum heat flux which can be emitted from the heated surface and therefore the heat flux deliverable to the target surface, as per the 2nd law of thermodynamics. For focused IR heating, source temperature is the most prominent characteristic which defines the usefulness of the radiation emitted from the source.

In addition to the primary radiator of the tungsten, the quartz envelope will act as a secondary radiator but at a lower temperature and hence with a longer wavelength emission spectrum. At the upper operating temperatures of quartz (~ 1500 K [2]), the vast majority of the emitted radiation will be within the NIR and MIR wavelength regions.

From the filament of a QTH lamp, heat will be transported primarily by radiation, but a combination of convection and conduction will transfer a non-negligible amount of heat from the source to the ambient. Fig. 2.9 illustrates the mechanism of heat transfer within a QTH lamp with “radiation to ambient” assumed to transport the majority of the power

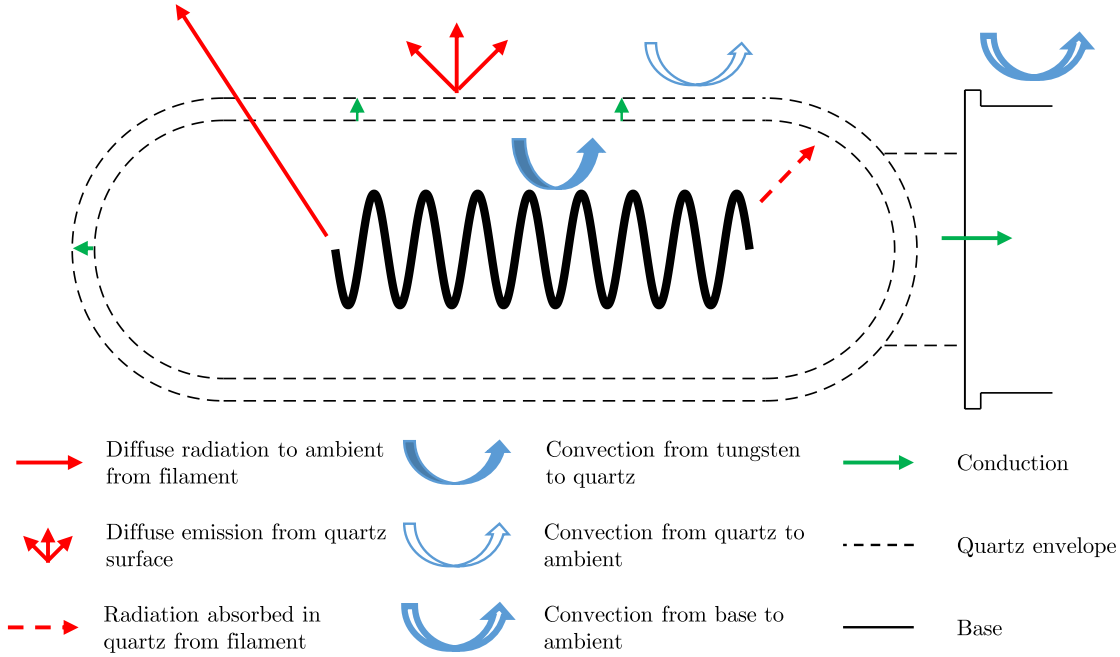


Figure 2.9: Representation of heat transfer within a QTH lamp from a filament to the ambient surroundings.

input to the surroundings. The radiative power output of a lamp can be determined by the product of the power input to the QTH lamp and the electric-radiative efficiency. However, the efficiency of this type of IR source has not yet been studied in detail. Bedard [35] carried out a comprehensive characterisation of electric and gas-powered IR heaters regarding planar radiant heat flux mapping, radiant efficiency, and spectral emission. Bedard reported that the radiant efficiency of the IR sources varied between 34% and 90% and strongly depended on the type of heater used. Pettersson & Stenström [36] used an in-house transient model to predict radiative efficiencies in the range of 55% at low power and 86% at high power for a double-ended QTH lamp, although the efficiency was not experimentally validated. Besides these two bodies of research, there is yet to be a thorough investigation of the thermal performance of these IR sources; therefore, there is a significant gap in the literature which limits the understanding of these sources, and consequently, any device that employs them.

2.3.2 Tungsten filament and fill gas

Today, tungsten is the primary material employed as a filament due to its excellent mechanical and thermal properties at high temperature. Specifically, tungsten has the highest melting temperature of any unalloyed metal (~ 3650 K [37]), a low rate of evaporation, and preferable resistive properties for heating by the Joule effect. However, tungsten is brittle in its unalloyed state, which poses a significant challenge when drawing the thin filament

necessary for incandescent lamps. This obstacle was overcome by William D. Coolidge in 1906 when he developed a method of forming more ductile sintered tungsten, which can be drawn at lower temperatures than conventional tungsten [38]. This technique is still used today in the manufacture of tungsten filaments. Later, a scientist by the name of Langmuir discovered the benefits of using a coiled filament structure [28]. It was noted that the heat loss was proportional to the diameter of the coil, and not the diameter of the filament itself, which resulted in a paradigm shift in terms of the manufacturing of incandescent lamps. The efficiency of incandescent sources is further improved when the tungsten coil is again coiled to create a “coiled-coil” allowing a large surface area of tungsten to be fit into a small volume. An example of a drawn tungsten coiled-coil is shown in Fig. 2.10 using a magnified SEM image.

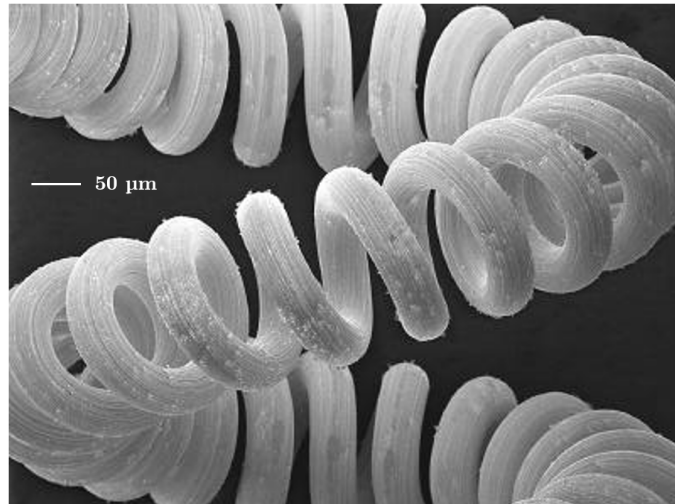


Figure 2.10: Scanning electron microscope image of a coiled-coil tungsten filament. Reproduced from [2], with the permission of the American Association of Physics Teachers.

A tungsten filament will begin emitting visible light when heated above 800 K [16] and will emit higher intensity radiation with a shorter wavelength distribution until its maximum prolonged operating temperature of ~ 3000 K. At this temperature, the peak wavelength of emission is $\sim 1 \mu\text{m}$. During startup at room temperature, the tungsten filament has a lower resistance by approximately a factor of 10 than when under steady-state operation. This implies that the initial inrush of current to the filament will be very high, which will lead to strong magnetic forces between the coils. If the coils come into near contact, a short can occur resulting in the degradation of the lamp’s lifespan. This can be avoided by using a preheating procedure with lower input voltages or a current limiting device [2, 32].

When a tungsten filament at high temperature is exposed to oxygen, it oxidises rapidly

forming a range of compounds (e.g. tungsten trioxide and tungsten dioxide) depending on the fraction of oxygen and the exact temperature of the process. Therefore, inert gases are sealed within the quartz envelope to prevent this reaction from occurring. Typical gases used in ascending order of cost are nitrogen, argon, xenon, and krypton. A mixture of nitrogen and argon are typically used with inexpensive lamps, whereas the premium fill gases xenon and krypton are used in more expensive lamps due to their retardation of the evaporation of the filament and lower thermal conductivity. These factors are noted to result in a more efficient lamp (due to the lower convective losses) and a longer-lasting filament.

2.3.3 The halogen cycle

Due to the high operating temperatures of the filament, the tungsten will sublime from its solid phase directly to gas (referred to as evaporation from herein). The tungsten gas will solidify on the inside surface of the cooler quartz envelope, causing a black deposit to form on the inner surface and degrade the radiation output of the lamp. This can be resolved by adding a small fraction of halide to the fill gas to allow the halogen cycle to take place.

Halides are a group of periodic elements which includes fluoride, chloride, bromide, and iodide. Bromide is the typical gas used in contemporary halogen lamps. The halogen cycle allows the evaporated tungsten to react with the added gas and form tungsten halide which can subsequently be returned to the filament surface where it dissociates and redeposits, restoring the filament. This process is illustrated in Fig. 2.11. The initial formation reaction occurs in the colder areas of the lamp near the envelope once the temperature of the envelope is maintained above 200-250°C [40]. The dissociation occurs in the hottest areas of the lamp near the filament surface. The halogen cycle increases the lifespan of the lamps and allows the filament to be operated at a higher temperature with resultant higher efficiencies and radiation intensity outputs. However, even with the halogen cycle, lamp filaments will still fail eventually due to factors such as hotspot growth [41], chemical attacks, and thermal limitations of the hermetic seal [28]. Further details of the halogen cycle can be found in Chapter 4 of reference [28].

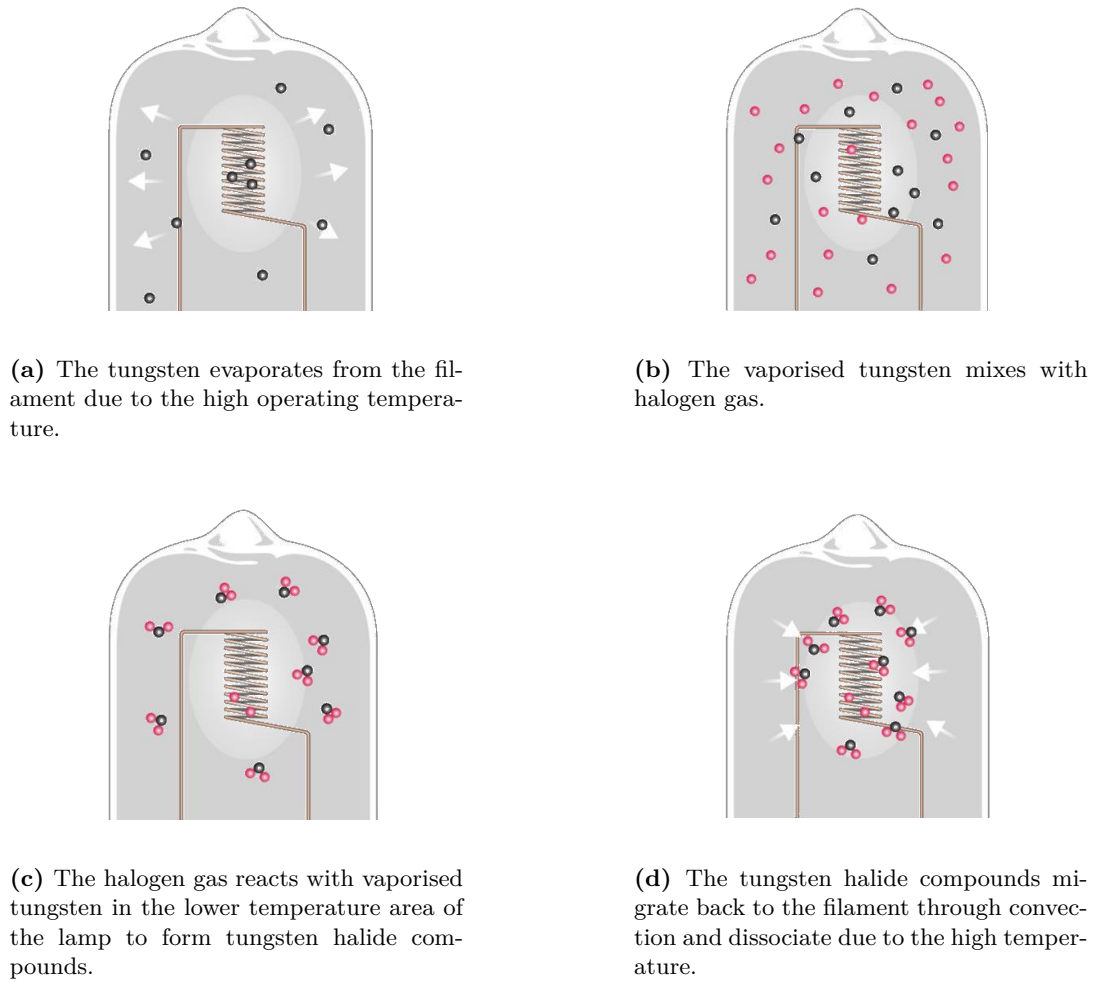


Figure 2.11: An illustration of the halogen cycle. Adapted from [39].

2.3.4 Quartz envelope

The enclosing envelopes for halogen lamps are manufactured from quartz (SiO_2). This material is chosen for several reasons such as its high melting temperature, high transmissivity in the visible and NIR wavelength range, hardness and scratch resistance, cost-effectiveness, and mechanical stability at extreme temperatures. Other materials which have wider transmission windows in the NIR and FIR such as sapphire, Calcium Fluoride, and Zinc Selenide are not used in mass production due to prohibitively high costs.

There are four types of quartz, which are produced using various manufacturing strategies. A detailed description of each process can be found in reference [42]. Quartz envelopes are typically $\sim 1\text{-}2$ mm thick to withstand the force from the pressurised fill gas. Standard operating pressures for these lamps are often in the range of 3-4 bar above atmospheric [43]

although this may vary depending on the lamp design.

2.3.5 Light recycling

The process of light recycling can be described as a method by which the radiance of a source can be artificially increased in exchange for a reduction in source power output. This can be achieved by diverting the radiation emitted in a direction which is not useful back towards the source. An example is illustrated in Fig. 2.12 where a hemispherical mirror reflects radiation emitted from an arc lamp back towards the emission point. The radiation transmitted through the source is superimposed onto the “phase space” of the source and therefore leads to an increase in the effective radiance. Phase space is characterised by the angular and spatial dimensions of the radiation at a given point in the system and is a measure of the quality of the radiation. The concept of phase space will be expanded upon in section 2.5.3.

Radiation can also be reflected on a heated surface (e.g. a filament), causing an increase in the radiance. This can be conceptualised as increasing the radiosity of the source since radiosity is the sum of the emitted and reflected radiation. Since the tungsten filament is coiled and is therefore concave, the benefits of light recycling can be realised even without employing a reflector. In the work of *Fu et al.* [44], it was shown that light recycling for a tungsten filament with a single-coil could increase the effective emissivity of the source by $\sim 30\%$. Fig. 2.13 shows the brightness enhancement on the inside of the coil of a QTH lamp due to the effect of light recycling. Presently, no data exists for a coiled-coiled filament besides *Ojanen et al.* [45] who roughly estimated the light recycling factor to be 0.5 ± 0.1 .

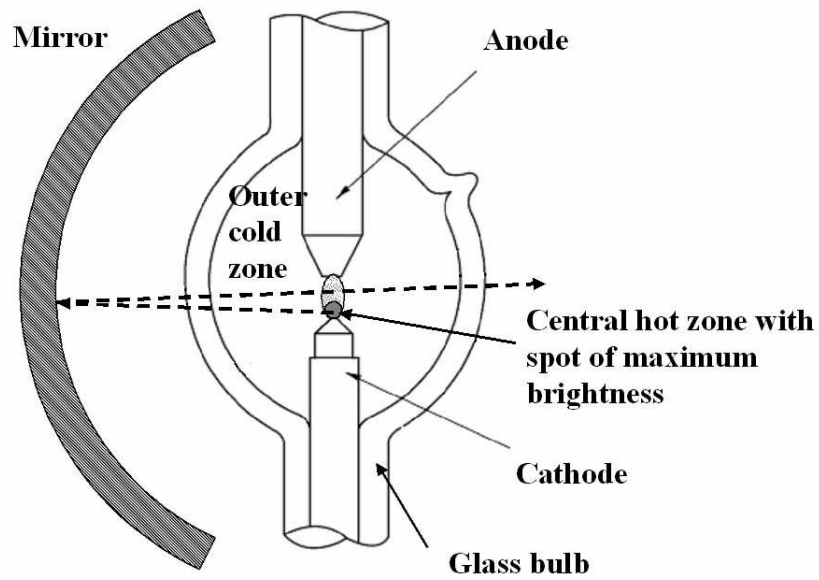


Figure 2.12: Schematic of a short-arc lamp with a hemispherical recycling mirror, including the path of a light ray retro-reflected from the brightest zone [46].

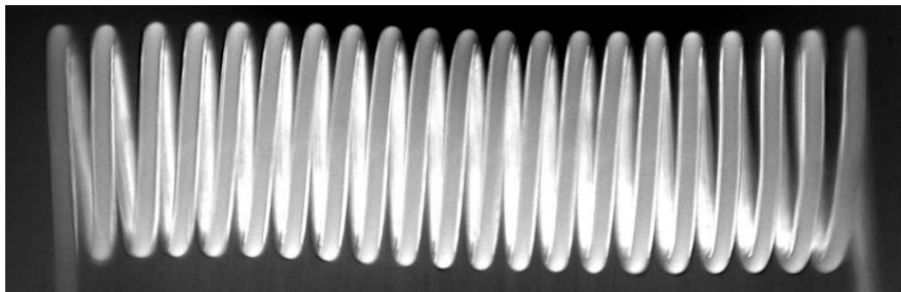


Figure 2.13: Light recycling enhancing the brightness of the inside coils of a tungsten filament [47].

2.4 Focused infrared heating technology

Focused IR heating is a subset of IR heating technology that employs lenses and metallic reflectors to concentrate radiation emitted from a high-temperature source. A significant body of work can be found in the literature on the modelling and development of defocused heaters [12, 36, 43, 48–54]; however, comparatively little is available in terms of the design and development of focused infrared devices [55–58]. Despite this, focused infrared heating is an area of interest for several applications such as soldering [11], brazing [59], fabrication of coated conductors [57], high strength steel forming [60], vacuum heating, and localised heating of samples [61]. QTH lamps are the most commonly employed sources for FIRHs due to the characteristics previously discussed, such as high filament temperature and long operational life.

A drawback of focused IR sources is the asymmetry and “extended” nature (i.e. nonzero length and width) of commercially available QTH radiation sources. Radiation is emitted in all directions from a nonpoint source and it is therefore difficult to achieve high power densities with any optics or reflector shapes, particularly with “off the shelf” shapes. Low power densities imply longer heating times, lower productivity and fewer applications where these devices can be used.

Two alternative technologies which compete for market share with IR heating are arc lamps and lasers. Arc lamps emit radiation by electrically arcing between metal electrodes in a contained atmosphere of a specialised gas at high temperature (~ 6000 K). Arc lamps emit “higher quality” radiation when compared to IR sources due to the greater emission temperature and smaller source extent, which is a considerable advantage; however, since this source operates at higher temperatures, a non-negligible proportion of the radiation is emitted in the UV waveband, which poses a health risk to its operators. Safety is also a concern with arc lamps due to the higher operating pressures and temperatures. A typical cost for these sources is in the range of ~ 1 \$/W, which is almost an order of magnitude greater than IR sources at $< \$0.2/\text{W}$ [62].

Lasers, on the other hand, emit coherent and monochromatic radiation from an amplified source with low beam divergence, implying they can be used with a range of optics or directed to distant targets effectively. These features also pose significant risks to its operators. Laser technology has reduced in cost since inception but is still significantly more expensive when compared to focused IR or arc lamps. Fig. 2.14 shows a comparison between the costs of

various lasers systems and IR technology in terms of capital and running costs [62]. Although the costs of lasers may have reduced in the years since publication, overall it is clear that infrared is a much cheaper technology to acquire and operate when compared to lasers.

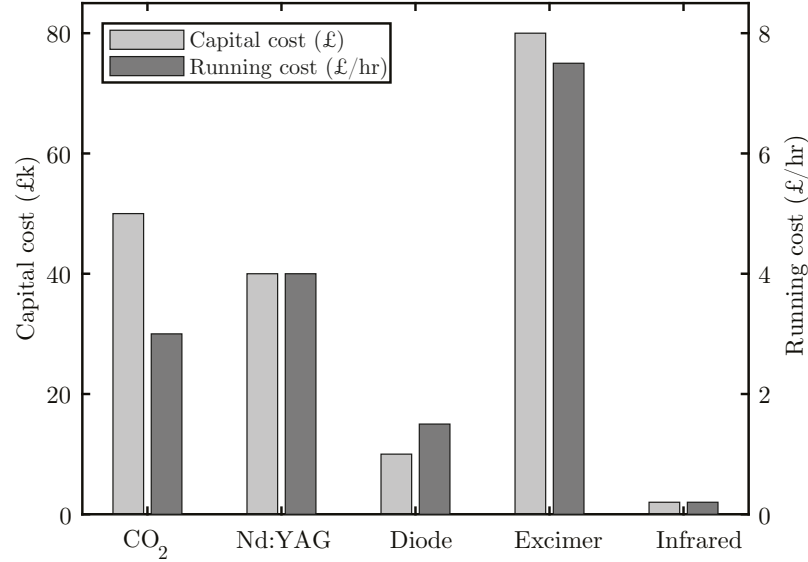


Figure 2.14: Estimated capital and running cost of lasers and IR heating systems based on a 1000 W power input [62].

2.4.1 Focusing radiation

2.4.1.1 A brief history of radiation manipulation

One of the first cases of radiation being intentionally focused was by Archimedes who allegedly set alight an enemy fleet during the siege of Syracuse in 212 B.C. by using an array of mirrors to concentrate solar radiation. However, the potential for this feat to be achieved with the technology available at the time is heavily debated [63]. Over 300 years later Diocles, a Greek mathematician, described a parabolic shape which could focus solar radiation, although little of his original work has survived the almost two millennia since.

The first well-documented case of mirrors being used for light concentration was in the 10th century by the Arabian mathematician Ibn Sahl with his work on burning mirrors and lenses [64]. Sahl demonstrated how parabolas and plane convex lenses could be used to focus parallel rays, and how ellipses and bi-convex lenses can be used to focus rays from a small source. More recently in the 19th century, parabolas were used in the construction of lighthouses allowing the light emitted from a source to be directed towards incoming ships,

which increases the brightness of the source from the point of view of an observer. In the same century, ellipses were patented for use in luminaires by A. Wilhelm [65]. Custom reflector shapes began to emerge from the 1930s onwards with several patents and publications which describe the techniques used to develop these shapes. These so-called “freeform reflectors” were designed to achieve a specific illumination distribution on a target surface. At this time, the actual source could not be modelled and required the simplification of its geometry to a point. The general reflector equation was posed in 1932 by Boldyrev [66], which if solved, would allow a reflector shape to be found for a wide range of desired illumination distributions. However, this equation proved extremely difficult to solve until many decades later, when robust solutions were posed using numerical methods by Ries and Muschaweck [67].

In the 1970s, the field of nonimaging optics (NIO) was incepted by Welford and Winston [68]. This area of research concerns the optimisation of the transfer of radiation from a source to a target without the need to form an image. This field was driven by the need to concentrate solar radiation, where higher concentration ratios allowed greater efficiencies to be obtained with smaller solar cell footprints. NIO techniques such as the edge ray theorem and the flow line method led to the development of many unique optical shapes. The most widely known of which is the compound parabolic concentrator (CPC), as shown in Fig. 2.15.

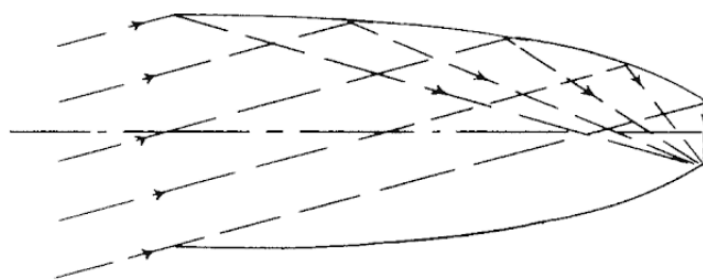


Figure 2.15: 2D compound parabolic concentrator [13].

In the decades since, freeform reflectors have been developed for extended tubular sources by *Muschaweck et al.* [69] and *Ong et al.* [70] using the edge ray theorem. Solar radiation has also been a focus of many different research groups with custom reflectors and mirrors developed using optimisation algorithms [71]. A considerable volume of work has followed in illumination design by various researchers, although this work is primarily directed towards

the illumination of large surfaces as opposed to the focusing of radiation over a small concentrated area. Moreover, most of the work neglects the complexities of the source such as the quartz envelope, which is particularly important for a FIRH where there may be many interactions with a given ray of radiation and the quartz.

Similar to illumination design, there are sizeable advantages to using a custom reflector shape with a FIRH. Given that the reflector will be designed with the source shape in mind, it will permit higher efficiencies to be obtained when compared to the standard shapes which are designed based on several assumptions. Furthermore, a custom shape allows the lamp inlet orifice to be tailored to that of the shape of the quartz base, increasing the reflective area of the enclosure. A body of work has been established on custom reflectors for illumination applications, but none yet for focused IR heating applications. Before delving deeper into the research of custom reflector shapes, the operation of conventional FIRH reflector shapes will be outlined in advance of discussion of the commercially available devices.

2.4.1.2 Parabolic reflectors

Parabolas can be utilised in two ways: by focusing parallel rays of radiation upon a small area (e.g. a parabolic solar trough) or in the opposite direction by transforming radiation emitted from a small source into a parallel beam (e.g. spotlight or a car headlight). The latter case is shown in Fig. 2.16a. The equation of a parabola is as follows:

$$(x - h)^2 = 4p(y - k) \quad (2.19)$$

Where h , p , and k are constants which define the shape of the ellipse. A well-collimated beam originating from an elliptical reflector can be focused upon a smaller area using an appropriate optical setup if so desired. However, the additional optics that are required to focus the collimated radiation to a small area and the absence of small extent, high powered IR sources are the primary reasons for the lack of development of this focusing technique. Parabolas are typically used in IR applications where heat is required to be distributed over a relatively large area [72].

2.4.1.3 Elliptical reflectors

An ellipse is a shape that surrounds two focal points which is defined by a minor and major axis length. Ellipses belong to the same family of shapes as a circle, with the equation of an

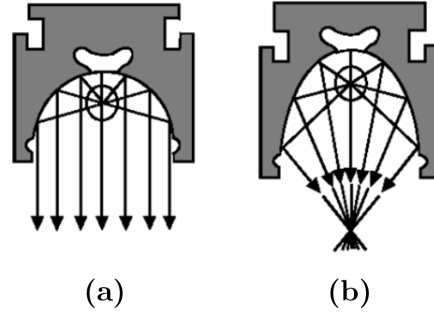


Figure 2.16: A point source with (a) parabolic and (b) elliptical reflector [73].

ellipse reducing to that of a circle when the minor and major axis length are equivalent:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (2.20)$$

If a point radiation source is placed at one focal point of the ellipse, the emitted radiation will be directed towards the second focal point, as shown in Fig. 2.16b. This reflector shape has been employed in the literature with waveguides [74], for the preheating of steel [12], and soldering [55]. Analytical measures of the performance of an ellipse have also recently been developed by Rehn [75].

The size of the area over which the radiation can be focused is a function of the extent of the source, with a bigger source resulting in larger focal areas. As with a parabolic reflector, a small error in the positioning of the source within an ellipse drastically decreases the efficiency of the transfer process [58], and therefore precise manufacturing tolerances are required for these shapes.

2.4.1.4 Lenses and optics

Lenses were investigated in the work of *Anguiano et al.* [55] where various setups were studied for use as an IR soldering station. The power output achieved in this study was sufficient for soldering, yet was significantly lower than what is required for other focused IR applications, with power densities of less than 50 W/cm². As a result of the low power density achievable when using lenses, they are not utilised in the commercially available focused IR units. The reasons for the low power density can be attributed to the following factors:

1. The poor collimation of the rays from IR sources due to the extent of the filament.

2. Errors due to chromatic aberrations.
3. The additional expense and size of the IR devices associated with these lenses.
4. Losses due to absorption and Fresnel reflections at the interfaces of the lens.

2.4.2 Commercially available FIRHs

There are many spot heaters currently available on the FIRH market. These devices are often used for soldering rework stations and metal/polymer heat treatments. The focused spot heaters have a radiant spot size in the range of 2 mm to 30 mm depending on the application with smaller spots typically used for soldering applications and the larger spots used for surface heat treatments, heating equipment, and the high-temperature testing of components. The reflector shapes employed fall into two broad categories of *closed shapes*, such as the reflectors shown in figures 2.17a and b, or *open shapes*, such as the semiellipse shown in Fig. 2.17c. There are advantages and drawbacks associated with both designs. The open shapes are capable of directing radiation at a target from a distance but at the expense of a larger heated area and reduced heat flux. Conversely, closed shapes have a well-defined heated area and will have higher heat flux outputs, but this comes at the cost of having to locate the reflector exit or guide rod close to the target surface. The most relevant commercial units are briefly outlined in the following paragraphs.

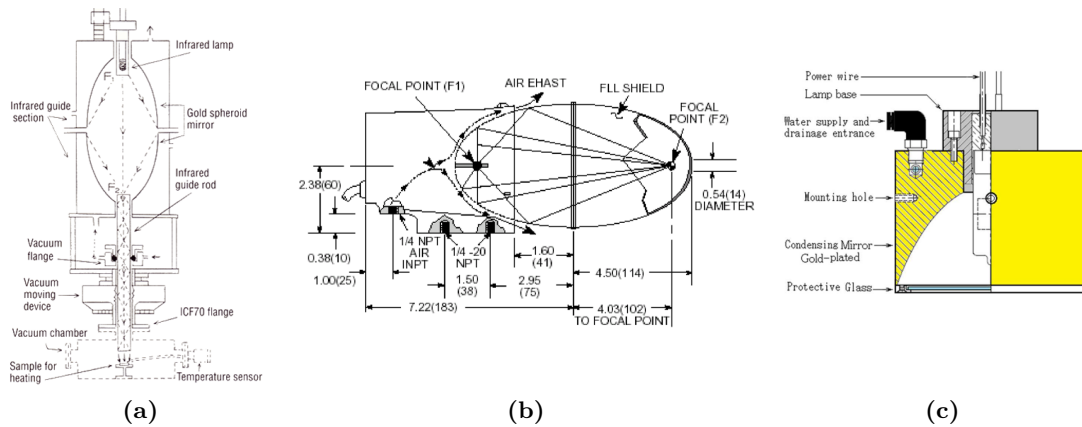


Figure 2.17: A selection of commercial FIRHs: (a) Thermo Riko GVL398, (b) PCS controls 750 W spot heater, (c) Heat Tech HPH-160 open reflector.

Thermo Riko is a Japanese company which provides a range of high-cost spot heaters for both research [34] and industrial applications. The details of several of the high-cost focused IR heaters supplied by this company are provided in Table 2.1. The GVL398 is one

of the most-powerful devices found on the market with a cost of over \$20,000. A schematic of this device is shown in Fig. 2.17a. This device requires an electrical power input of 3000 W, and the radiation is focused using a gold-coated spheroid (3D ellipse) reflector. A quartz rod is inserted at the second focal point of the closed ellipse which captures the radiation output. Working distances of <3 mm from the quartz guide rod exit to the heater surface are required for all of the devices supplied by Thermo Riko. These units are quite large, with an overall length of over 700 mm, although this includes the quartz guide rod and accompanying assembly.

Heat Tech is a second Japanese company which has developed many elliptical reflectors capable of focussing IR radiation upon areas ranging from 1.5 mm to 60 mm in diameter. These units employ an Au-coated semiellipse, with water or air cooling to maintain a low reflector temperature. The HPH-160 (shown in Fig. 2.17c) reflector delivers the greatest heat flux output from a high powered commercial unit with a specified peak value of 180 W/cm^2 according to the manufacturer, although the technique used to determine this value was not specified. Fig. 2.18 shows the difference between a peak and an average heat flux output, and thus for this unit, the average heat flux over the entire spot size will likely be considerably lower than the specified peak value. Since the focal distance (distance from the heater body to the target surface) for this unit is quite small at 40 mm with a reflector outlet diameter of 160 mm, it is geometrically challenging to couple multiple units to produce a higher intensity spot. Furthermore, given that this shape is open, achieving extremely high heat flux outputs will be substantially more difficult than a closed reflector shape, which will recycle radiation that does not intersect the target surface.

PCS manufactures a 750 W SpotIR heater which uses an open or closed elliptical reflector (selected by the user) with a polished aluminium surface. The device costs \$1,790, which is comparatively much less than other systems discussed. The peak heat flux output is specified to be over 100 W/cm^2 in the device's documentation, but the average will be much lower when considered over the entire 14 mm diameter outlet. PCS also provides a 250 W version of this unit which is stated to have a peak heat flux output of 170 W/cm^2 but with much lower power output, thereby limiting the number of applications suitable for this device.

Thonauer manufactures a series of "Lightbeam" spot heaters which are predominantly used for soldering applications. The most powerful device is supplied with 1000 W and has a focal distance of 5-6 cm from the bottom surface of the open elliptical reflector. The diameter of the reflector is 10 cm, and the beam is focused over a $2\text{-}3 \text{ cm}^2$ area depending

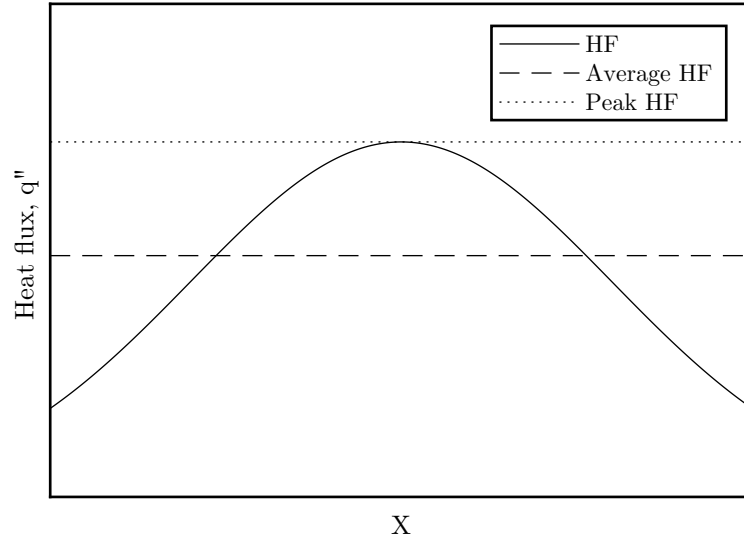


Figure 2.18: Illustration of the difference between a peak heat flux and average heat flux for a FIRH.

on the reflector system used. The power output of the device is in the range of 45 W. The primary drawback of this particular device is that the power output within this area is far too low for the needs of many applications although it does have the benefit of a large focal distance which means there is potential to employ multiple units to heat the same spot. The highest heat flux from any device in this series has over 170 W/cm² output; however, this is accompanied by a power output of only 12.5 W and thus is not suitable for applications that require high power (such as metal annealing).

A comprehensive list of commercially available FIRHs is provided in Table 2.1. As shown, there is a wide range of spot sizes, efficiencies, and heat fluxes delivered. The efficiency or heat flux output of the device may appear to be an ideal choice for comparing FIRHs from various manufacturers; however, previous work by the author indicates that there is a trade-off between efficiency and heat flux when changing the relative size of the outlet and source: large exits tend to lead to higher efficiencies and lower heat fluxes while smaller exits tend to lead to lower efficiencies and higher heat fluxes. Thus, it is not possible to compare the performance of reflectors using the standard metrics currently presented in the literature. This is a gap in the literature that will be addressed later in this work in section 8.5.

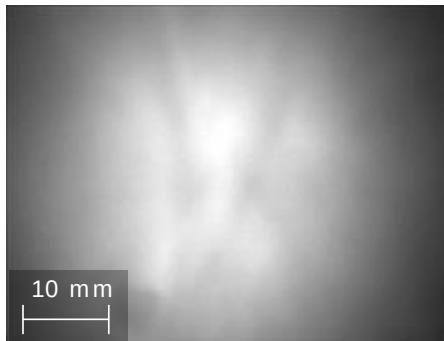
2.4. Focused infrared heating technology

Table 2.1: Commercially available focused IR heaters [14]. Heat flux specifications have been denoted as either peak (P) or average (A) to indicate the measurement type.

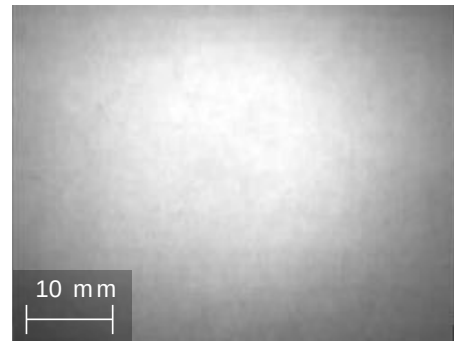
Manufacturer	Device	Cost	Power Input (W)	Power output (W)	Efficiency	Spot diameter (cm)	Power density (W/cm ²)	Illuminated area (cm ²)	Comment
PCS	SpotIR 4085	\$1,790	750	10	1%	0.635	32 (P)	0.3	No Shield
PCS	SpotIR 4085	\$1,790	750	19	2%	0.635	60 (P)	0.3	Partial shield
PCS	SpotIR 4085	\$1,790	750	32	4%	0.635	101 (P)	0.3	Full shield
PCS	SpotIR 4150	\$1,475	250	-	-	0.635	172 (P)	-	With heater collar
Thonauer	Lightbeam S250	-	150	9	6%	0.3	127 (A)	0.1	Soldering machine
Thonauer	Lightbeam S250	-	250	12.5	5%	0.3	177 (A)	0.1	Soldering machine
Thonauer	Lightbeam S1000	-	400	33	8%	2	11 (A)	3.1	Soldering machine
Thonauer	Lightbeam S1000	-	1000	43	4%	2	14 (A)	3.1	Soldering machine
Optron	600.5100.1	-	150	27	18%	1	34 (A)	0.8	-
Optron	600.5123 / 4	-	150	24	16%	0.6	85 (A)	0.3	With additional reflector
Thermo Riko	GV 198	-	1000	275	28%	2	88 (A)	3.1	Estimated power from TR
Thermo Riko	GV 298	-	2000	317.5	16%	2	101 (A)	3.1	Estimated power from TR
Thermo Riko	GVL 398	\$20,000	3000	350	12%	2	111 (A)	3.1	Estimated power from TR
Heat-tech	HPH-160	-	3000	-	-	2.4	180 (P)	-	
Heat-tech	HPH-120	-	1000	-	-	1.8	120 (P)	-	

2.4.2.1 FIRHs in research

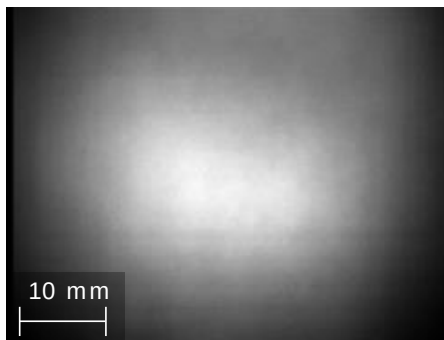
There are several FIRHs which have been developed for use in research [11, 55]. Four IR soldering setups were tested in the research by *Anguiano et al.* [55] using an Au-coated parabolic reflector and various condenser lens setups. A QTH lamp (OSRAM model 64635 HLX) was used as the power source with a 150 W electrical power input. The power concentrated on the target was measured on a BGA SMT device which provides a heat flux map of the incident radiation. Temperatures required for soldering ($<230^{\circ}\text{C}$) were achieved with the use of a complementary back-heating device which provided a starting temperature of $40\text{--}60^{\circ}\text{C}$ before the FIRH was powered. Heat fluxes of $\sim 50\text{ W/cm}^2$ and uniform temperature distribution were delivered, although over a large area of $\sim 50 \times 50\text{ mm}$, as shown in Fig. 2.19. In order to improve the heat flux output, several of these devices could be coupled to create a higher intensity spot. Despite the small source, the area over which the radiation is focused is too large for many of the applications considered in this work.



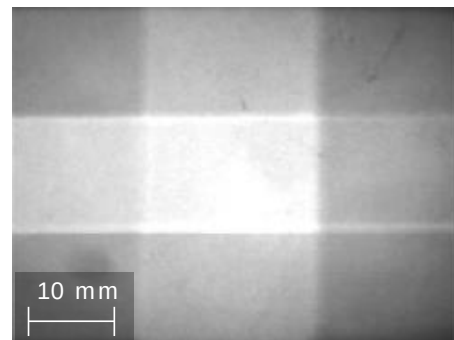
(a) Basic optical setup.



(b) Optical setup with ground glass diffuser homogeniser.



(c) Optical setup based on a nonimaging homogeniser.



(d) Optical setup based on an imaging homogeniser.

Figure 2.19: Irradiance maps for various optical setups in the experiments by *Anguiano et al.* [55].

The application of IR heating to reduce springback during forming operations on high

strength steels was studied by *Lee et al.* [60] with respect to temperature, the effect on material microstructure, and springback after forming. Springback is the unwanted geometric change of a part after a forming process which tends to return the part to its original shape. The study employed two different IR heaters, one focused (ellipse) and one defocused (parabola), both using a lamp with 26.7 W/mm power per unit length. Both the focused and defocused IR heater delivered advantages when compared to furnace preheating or no heating at all. The rapid preheating process reduced springback, and improved processing times with negligible changes in microstructure when compared to furnace preheating.

2.4.3 Focused IR applications

There are several other applications which are suitable for FIRH technology, particularly if improved performance can be garnered from these devices.

2.4.3.1 Cold spray

As discussed in the Introduction, Cold Spray (CS) is a coating and additive manufacturing (AM) technique where metal powders are accelerated to supersonic speeds using a De Laval nozzle before impacting upon a substrate [8]. The kinetic energy of the particles upon impact causes substantial plastic deformation of both the particle and substrate, allowing bonding to occur through mechanical interlocking and adiabatic shear instability [76]. CS allows coatings to be manufactured which show little oxide inclusion, present low porosity, and are free from melting and therefore exhibit similar microstructure to the feedstock powder. A schematic of the cold spray process is shown in Fig. 2.20.

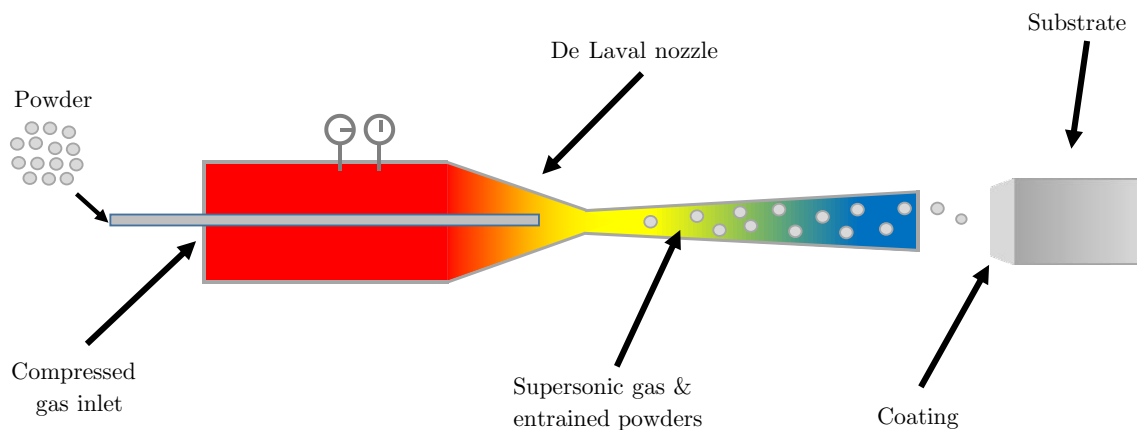


Figure 2.20: The cold spray process [77].

CS samples are often more brittle when compared to bulk counterparts due to the strain hardening that occurs during deposition. This dramatically affects the fatigue strength of the coatings and their suitability for mechanically stressed applications. Therefore, heat treatment processes are often used to improve the overall mechanical properties of CSed coatings. In-process heat treatment of CS coatings has been suggested as a method which can improve the mechanical properties of the coating more rapidly than conventional heat treatments [10, 78].

2.4.3.2 High-temperature component testing

As outlined in the early work by Hanson and Casey [79], there is a specific need for low cost, high-temperature test equipment. A myriad of applications require the high-temperature testing of materials such as plasma-facing components [50], the temperature cycling of orbital equipment [80], and supersonic aircraft/re-entry vehicles thermal protection [81]. The high-temperature testing outlined by Hanson and Casey was over large areas of supersonic aircraft and hence can be described as defocused IR testing. However, there are still many potential applications that require contactless testing of small components at a higher temperature, and lower cost than the incumbent technology allows.

2.4.3.3 Composite and polymer processing

The market for laser diode materials processing was over \$300 million in 2014, with a predicted growth of 13.5% per annum, taking it to over \$700 million by 2020 [14]. The typical applications of a diode laser include bonding, curing of polymers and adhesives, and polymer welding. This area has yet to be widely permeated by FIRHs; nonetheless, FIRHs would be suitable if power densities equivalent to low or mid powered diode lasers could be delivered.

2.4.3.4 Laboratory heating equipment

Heating equipment for laboratories is a market segment which is well catered for by Thermo Riko [34]. Since this product is suitable for not only heating in ambient conditions but also within vacuum systems, there are many uses for this FIRH as general lab equipment. However, higher-performing devices would prove even more useful.

2.4.3.5 In space heating

The testing of components at high temperature in space is a requirement for many missions for both the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). There are severe weight and volume limitations for any heating devices which can be transported into orbit due to the associated cost. It is estimated to cost at least \$2000/kg to launch into low earth orbit and significantly more for high earth orbit and beyond [82]. This limits the use of many types of lasers due to their large bulk and cooling requirements. Inexpensive, small, and lightweight IR devices are potentially a more appropriate solution for this particular application.

2.5 Reflector shape design

This section of the literature review will describe the techniques used to design reflectors, which is often referred to as “optomechanical” design. Designing a custom FIRH has not been performed in the literature; however, there are several related fields which can provide insight into viable design strategies for this problem. Firstly, nonimaging optic design techniques will be introduced, which involve the maximisation of radiation heat transfer from a source to a target. Next, illumination design strategies are discussed, which delve into the optimisation of custom reflectors to match a specific illumination distribution on the target surface. The optimisation of solar troughs and mirrors is also related to this area and thus will be reviewed. Finally, the various strategies adopted for the design of radiation enclosures will be examined.

The design of a reflector inherently relies on the ability to characterise the performance of a given shape in a time-efficient manner. Various modelling strategies are applied to allow the changes in a design to be quickly tested and the effect of these changes to be understood, without the need to manufacture and test a prototype. However, the modelling of radiation dominant problems is challenging, and therefore, this aspect of the research needs to be first addressed.

2.5.1 Radiation modelling

Solving heat transfer problems using traditional modelling methods proves difficult when taking into account radiation where fourth-power temperature relations govern the rate of heat transfer. To further complicate matters, the properties of materials are often a function of wavelength, direction, refractive index, and temperature. The energy balance required

when modelling this type of system typically takes the form of a nonlinear integro-differential equation so complex that in most practical cases, it cannot be solved by analytical means [83].

The first simplification often applied to heat transfer problems of this nature is to ignore radiative heat transfer entirely. This assumption is often reasonable when the absolute temperature is small ($<400\text{-}500\text{ K}$). However, given the temperature of the IR emitter, this option can be disregarded.

Secondly, simplifying assumptions regarding the radiative properties can be made to reduce the complexity of the problem while accepting there will be an inherent loss of accuracy. It may be assumed that the surface is black, grey, diffuse, or specular in nature or a bulk material is transparent, for example. In some cases, grey band models can be used, which allow the discretisation of the spectral distribution into a series of bands with constant material properties. However, the computational expense of doing so is often considerable. In the case of a problem that has widely varying surface and bulk properties, none of the assumptions listed can be applied without a considerable impact on the accuracy of the model.

Only in recent decades have methods developed such as discrete ordinates [84], the P1 method [85], and the discrete transfer method [86] which allow the radiative transfer equation to be solved through numerical integration of a discretised domain. However, these solutions are typically challenging to implement with complex geometry and particularly with geometry that is not predefined. Moreover, many of these methods require simplifying assumptions such as those listed above. An alternative modelling method which is not subject to these issues is the Monte Carlo (MC) technique, which can now be introduced before delving into the literature on FIRH design strategies.

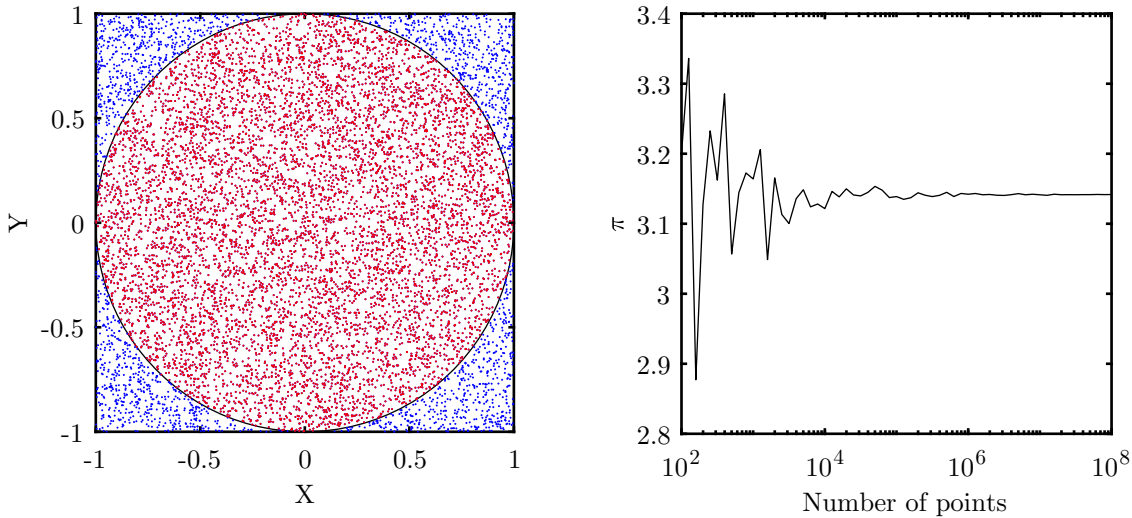
2.5.2 The Monte Carlo method

The MC method was eloquently described by John R. Howell [87] when he stated that “Monte Carlo has been defined as the technique of solving a problem by putting in random numbers and getting out random answers”. Although this might seem like a senseless method where the answer is dependent on randomness, it is quite the opposite. The MC method transforms statistical randomness into valuable information which can be used to evaluate problems that are otherwise difficult or near impossible to solve using alternative approaches.

The MC method was first developed by researchers working on the atomic bomb as a method to model and understand the complex statistical nature of the interactions between

neutrons just before criticality is reached. This was a highly suitable application because interactions between neutrons can be accurately defined by probability distributions [88]. In short, the MC method is essentially a sampling integration method that can tackle the complex problem formulation of radiation heat transfer based problems with relative ease.

A simplified example of the MC method applied to the estimation of π is shown in Fig. 2.21. By generating random points in the square of the $x \in [-1, 1]$ and $y \in [-1, 1]$ domain, π can be estimated based on the number of points which fall outside of this circular boundary in comparison to the total number of points seeded. Fig. 2.21b shows the convergence of the MC method as the number of sample points is increased.



(a) Ten thousand points randomly distributed between $x \in [-1, 1]$ and $y \in [-1, 1]$ with the accepted points in red and the rejected points in blue. (b) The convergence of the MC method to π as the number of samples is increased.

Figure 2.21: Estimating π using the MC method.

As shown in Fig. 2.21b, when a small number of points are sampled, the variance is quite significant. Variance reduction methods can be used to reduce the statistical error of the MC method and allow fewer seed points to be used. One class of variance reduction methods involves adjusting the sampling strategy to ensure that the domain is more evenly “integrated”. Two examples of this are presented in Fig. 2.22 which are referred to as stratified sampling and the quasi-MC (QMC) method of uniform sampling. Quasi refers to the use of a deterministic method to represent an ideal random distribution. As shown, the random sampling technique produces an uneven distribution, whereas the stratified sampling shows a more even coverage of the domain. Wherever possible quasi-random sampling techniques

should be used to ensure a more even coverage of the domain; however, depending on the type of problem investigated, this may not be possible. A stratified sampling technique may be used where a quasi-random technique cannot. In practice, many MC simulations are not entirely random and instead employ a combination of random and deterministic approaches.

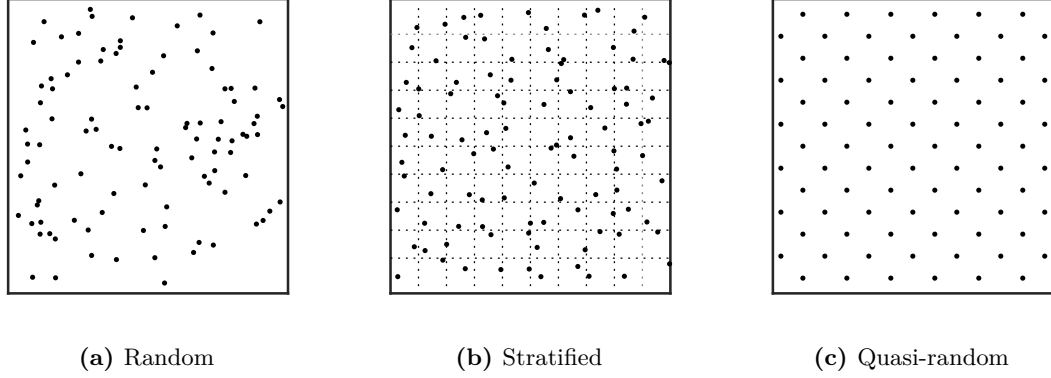


Figure 2.22: Comparison of seeding methods for the MC method. Adapted from [22].

For the simulation of radiative heat transfer, the MC method is coupled with the ray tracing (RT) approach, which results in a commonly applied technique referred to as Monte Carlo Ray Tracing (MCRT). RT is a modelling technique that is most often recognised for the generation of photorealistic images through the simulation of light transport [89]. Ray tracing is an equally suitable approach for the simulation of the transport of photons across the entire electromagnetic spectrum. Using this method, a particle or wave emitted from a heated body is simulated by a ray which propagates through space until interacting with an opaque body or a transparent interface. Based on the properties of the surface, the ray may then be reflected, transmitted or absorbed. At each interaction of a ray and surface or interface, the MC method is then applied to determine if the ray is absorbed, transmitted, or reflected based on the known properties of the ray and the material (i.e. wavelength, reflectivity, surface roughness). In summary, RT is the concept of following an emitted ray from a source until it is absorbed, while the MC method is used to select the outcome of ray interactions with the domain using statistical methods. Reference [22] can be consulted for a detailed discussion on RT and the MC method to simulate radiative heat transfer.

The use of the MCRT technique circumvents the need for a traditional integration of the governing equations. As a result, the computation time no longer scales linearly with the complexity of the domain, and a range of problems which are not suitable for standard techniques can now be tackled with ease. Due to the robust ability to accurately model

complex problems, the MC method is often used as an “exact” reference to which other radiative heat transfer solution methods are compared [90]. The MC method does, however, typically have a more intensive computational requirement when compared to traditional integration based modelling strategies, particularly when simulating trivial problems which can be simulated more easily using analytical methods.

2.5.3 Nonimaging optics design techniques

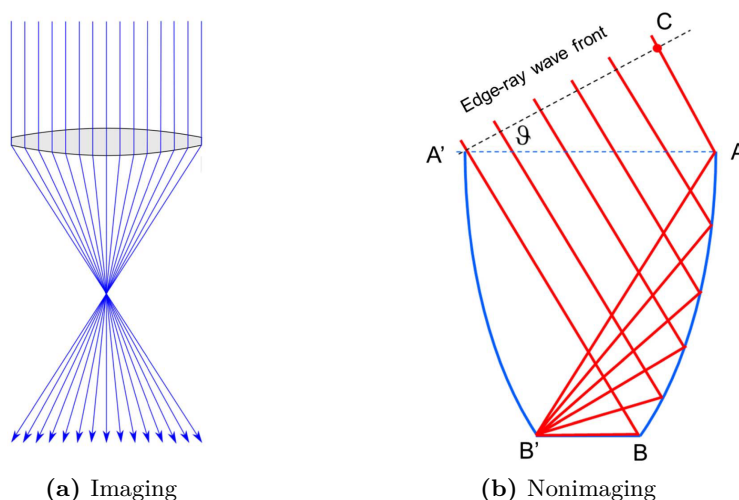


Figure 2.23: Comparison of two optical design approaches [20].

NIO is a field of engineering which studies the optimisation of radiative heat transfer from a source to a target without consideration for the preservation of an image. When an image must be maintained on the target surface (for example, photography or video recording), the choice of suitable optics is limited to those which do not cause aberrations of the transmitted beam. As a result of this restriction, there is a rather low limit on theoretical maximum efficiency. However, upon the advent of the field of NIO, a new design technique became available to engineers and designers which has no consideration for the output image or the problems associated with aberrations in conventional optical design. Instead, the goal is related to energy transfer, where the radiation output of the optical system is maximised relative to the input. An example of the difference between imaging and NIO is shown in Fig. 2.23.

The concentrators designed with NIO techniques deliver significantly higher efficiencies and in some cases can approach the theoretical thermodynamic limit. The lack of a requirement to form an image also means less precise optics can be used, and there is a higher

tolerance for error in shape and placement of the optics. Smaller and fewer lenses can be utilised and therefore NIO systems are often more economical when compared to imaging counterparts.

An ideal concentrator is shown in Fig. 2.24 where a combination of optics (i.e. reflectors or lenses) allows the radiation entering on the left-hand side to be concentrated into a smaller area through the exit on the right-hand side. To concentrate the radiation, the divergent angle at the exit of the concentrator must be larger than that of the entrance. This allows the area of the beam to be reduced while conserving étendue. Étendue is a fundamental topic to NIO and radiation heat transfer design as a whole, which can now be introduced.

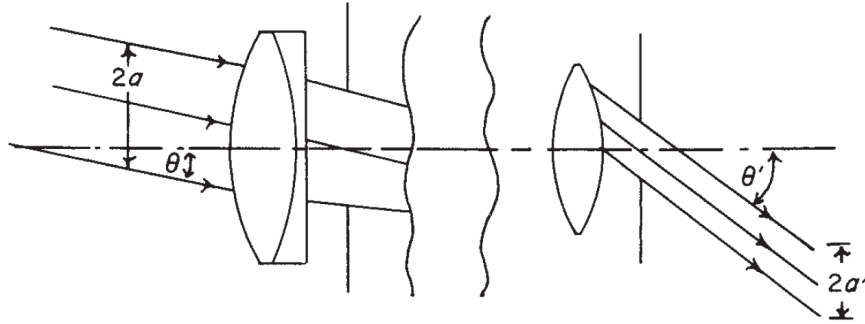


Figure 2.24: The étendue for a multielement optical system [13].

2.5.3.1 Étendue and phase space

Étendue or the closely related topic of phase space is a property of an optical system which is a measure of the quality of the radiation at a given point in that system. One of the first uses of this concept as a design tool was in 1996 by Brennesholtz [91] who employed it to characterise a series of projector systems. The formal definition of étendue is [91]:

$$\dot{E} = \int \int \cos\theta dA d\Omega \text{ (mm}^2\text{sr)} \quad (2.21)$$

When Eq. 2.21 is integrated, the product area and the solid angle (sr) of emission of the radiation is found.

Phase space is a four-dimensional volume which is defined using two spatial coordinates and two angular coordinates at a given interrogation plane. The two spatial coordinates define the location on that plane, and the angular coordinates define the solid angle. In 2D, phase space is described by a single positional coordinate and an angular coordinate on an interrogation line. The étendue and phase space of a system are related through the

refractive index of the material in question:

$$\acute{E} = P_s \times n^2 \quad (2.22)$$

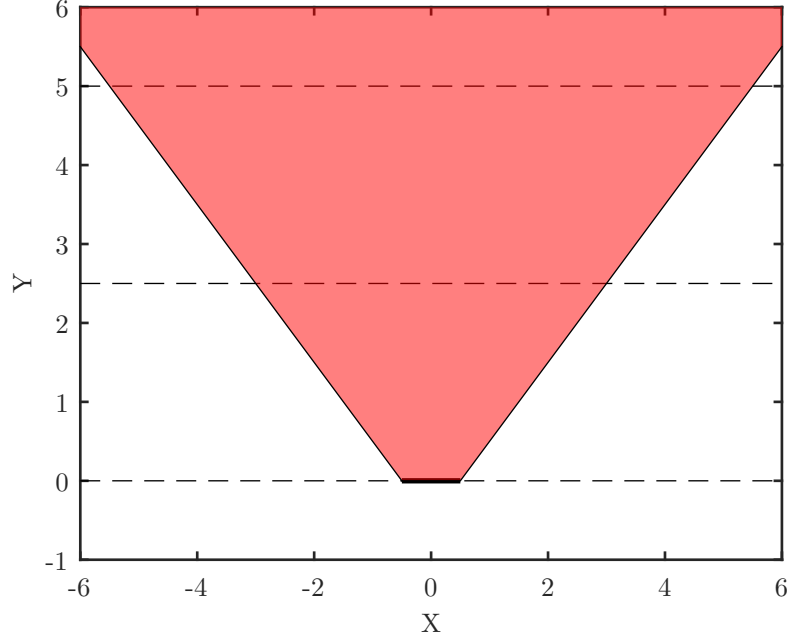
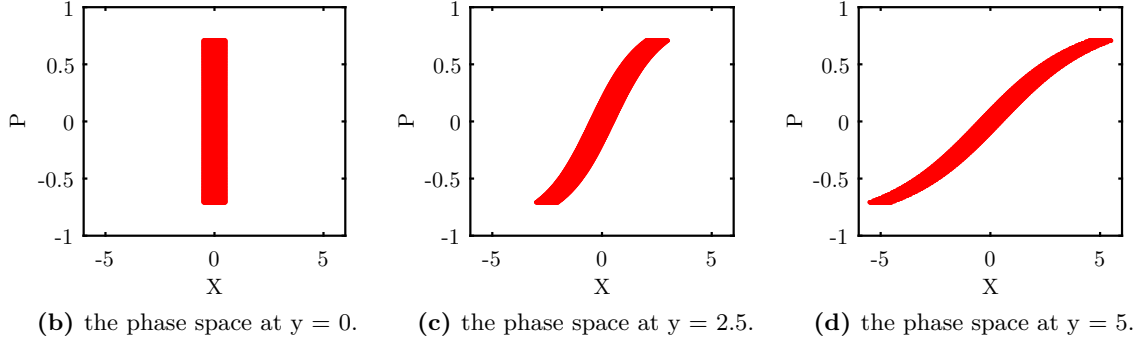
Thus for a material with a refractive index of one, phase space and étendue are equivalent. As a result, the terms phase space and étendue are used somewhat interchangeably. For clarity, in this work, the term phase space will be used to describe the “shape” of the radiation on a phase diagram, whereas étendue will be used to describe the unit of measurement.

Consider the example shown in Fig. 2.25a, which illustrates a unit length 2D linear source emitting at an angle of $\pi/4$. In practice, this could be likened to an LED source or radiation passing through a small orifice. The propagating radiation is illustrated in red, and the locations to consider are marked with dotted lines at $y = 0, 2.5$ and 5 . Fig. 2.25b-d plots the phase space as the radiation propagates through each of these areas of interest. The x values on the graphs are simply the x coordinates at the interrogation lines, and P is the “optical momentum” which is defined by $\sin\theta$, where θ is the angle of the propagating radiation at that location [20]. Notably, the volume of the phase space does not change and is constant across any interrogation line (since this is an ideal system with no losses). Étendue is analogous to entropy in a thermodynamic system meaning that étendue must always remain constant or increase throughout a process [91]. For this reason phase space and étendue are often referred to as the “optical invariant”. An exception to this is the case where radiation is rejected from the target surface. In this case, the étendue of the rays exiting the system may be lower than that of the étendue of the source; however, when considering the system as a whole and including the rejected rays, the overall étendue cannot decrease.

The spatial coordinates of radiation emitted from a point source are equal at that point, and thus a point source has an étendue of zero. Similarly, for a parallel beam, the angle of the propagating rays are the equivalent, and thus the solid angle and étendue is zero. This illustrates why it is impossible to create a parallel beam from a nonpoint source: as the étendue from a nonpoint source is always greater than zero, the radiation cannot be directed to a parallel state, as that would result in a violation of the principle of étendue.

Étendue can be described by area $\times$ solid angle as measured from a circular orifice [93]:

$$\acute{E}_{aperture} = \pi \times r_{max}^2 \times \pi \times \sin^2(\theta_{max}) = \pi^2 \times r_{max}^2 \times \sin^2\theta_{max} \text{ (mm}^2\text{sr)} \quad (2.23)$$

(a) A 1 mm length surface emitting at an angle of $\pi/4$.(b) the phase space at $y = 0$.(c) the phase space at $y = 2.5$.(d) the phase space at $y = 5$.**Figure 2.25:** An example of how phase space changes with distance from a source. Adapted from [92].

where sr is the solid angle, which is a measure of the angle in 3D space. The inlet or outlet angle of the beam is θ_{max} and the outlet radius of r_{max} . The étendue of a cylindrical source can also be estimated to be:

$$\dot{E}_{source} = \pi^2 \times h \times D \text{ (mm}^2 \text{ sr)} \quad (2.24)$$

where h is the height of the cylinder and D is the diameter.

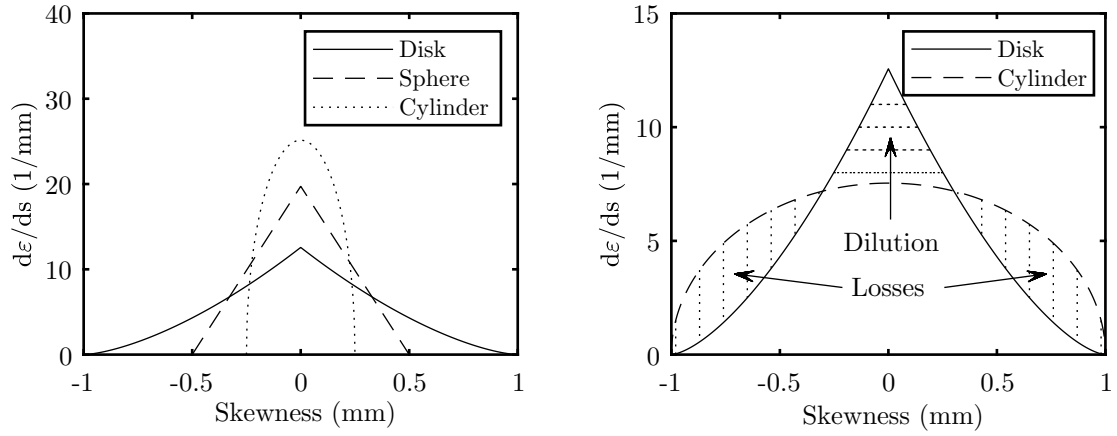
In Fig. 2.24, it was shown how étendue is conserved within the system, and as the area of the beam is decreased, the solid angle must increase. This trade-off is typically performed in order to maximise the heat flux on the target. The maximum angle which can be achieved at the exit is $\pi/2$, which sets the maximum permissible concentration ratio for a device

(without a change in refractive index) in 3D to the following [13]:

$$C_{max} = \frac{1}{\sin^2 \theta} \quad (2.25)$$

Here, θ is the beam's solid angle at the inlet. For the case of a Lambertian source (i.e. a QTH lamp) where the emission angle is already $\pi/2$, the maximum concentration ratio which can be achieved is unity under normal circumstances.

Differences between the shape of the source and the target can also affect the maximum permissible transfer efficiency [94]. Fig. 2.26a shows the different skewness distributions for a cylinder, sphere, and disc of equivalent surface areas and étendue. Fig. 2.26b illustrates the adverse effects of a skewness discrepancy between the source and target. The first effect is that the difference in shape lowers the permissible transfer efficiency. This is illustrated as the vertically shaded area outside of the disc target. Secondly, dilution occurs when the target is sufficiently large to receive the phase space of the source, but the shape of the phase space does not match that of the target. This results in a reduction in heat flux on the target surface. The unshaded area below the curves represents the phase space that can be transferred from the source to the target. When designing a radiation exchange system, the geometry of the target can be adjusted to ensure that all radiation can be efficiently transferred from the source to the target (i.e. there is no shaded region beneath the cylinder shown in Fig. 2.26b). However, this will cause dilution of the radiation and consequently, a reduction in heat flux on the target surface unless the shape of the target phase space matches that of the source.



(a) Skewness distribution of a disk with a radius of $R\sin(\theta) = 1$, a sphere of radius 0.5 and a cylinder of radius 0.25 and $H = 2$. (b) Illustration of dilution and étendue losses due to the discrepancy in the shape of the source and target.

Figure 2.26: Nonimaging optics analysis of a source and target. Adapted from [94].

2.5.3.2 Edge ray theorem

The edge ray theorem is a design concept that only considers the outermost rays entering a nonimaging optical system, which greatly simplifies the analysis. When the outermost rays from a source are transmitted through a concentration system and directed to the outermost point of the target, all of the internal rays will also be concentrated onto the target surface. An example of the edge ray construction of a compound parabolic concentrator (CPC) is shown in Fig. 2.27. A CPC is a device that concentrates radiation from a large inlet area to a smaller outlet area once the radiation entering the cone is within a given acceptance angle. These devices are often used with photovoltaic solar cells where higher intensity radiation can be directed to the cell, reducing the size of the cell and increasing the efficiency of the electricity generation process.

The outer rays (i.e. edge rays) of the source entering into the inlet aperture are used to determine the length and exit aperture size of the CPC. As shown in Fig. 2.27, a ray entering the inlet of the device at an angle of θ from A will intercept D, and a mirror image of this ray will enter at B and intercept C. The points A, B, C and D define the boundaries and the length of the CPC. The position of these boundaries can then be modified to change the permissible inlet angle and concentration ratio. After the edge rays have been used to design the shape, any ray that falls within the angle of the edge rays or aperture of the concentrator will be focused on the target surface.

The flow line method and the simultaneous multiple surface design method are two other

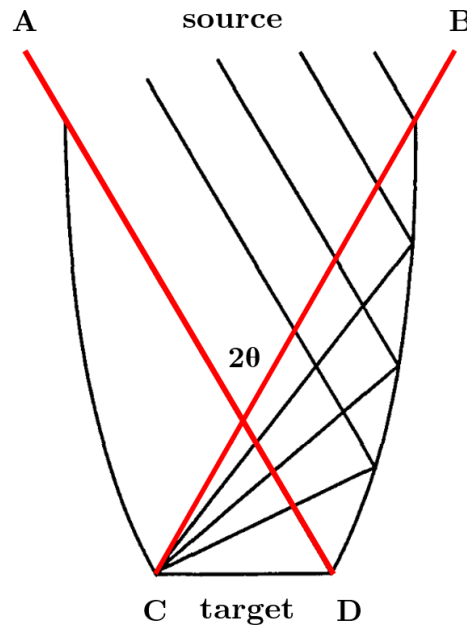


Figure 2.27: Edge ray principle for the design of a CPC. Adapted from [95].

design techniques which are used in the design of NIO. These methods are often used in 3D designs where the edge ray method falls short of ideal concentration. The details will not be discussed in this work, but comprehensive explanations can be found elsewhere [13, 96].

Several innovative solutions have arisen from research in NIO, which are related to the goal of this work. In 1998, *Feuermann et al.* [97] developed a NIO device that can transfer radiation from a small radiating source to a target using concentrating lenses and fibre optics. The version of this device developed for 2D sources (i.e. a linear QTH lamp) is shown in Fig. 2.28a but a similar concept for a 3D version was also presented. This device collects radiation from each of the six NIO concentrators into fibre optics and feeds the radiation into a remote luminaire. It was estimated that up to 75% of the radiation emitted from the source could be transferred to the target including the effects of packing losses of the fibre optics, lens, reflection, end, and transmission losses. This device was patented in 2002, but there does not appear to be a working prototype or any follow on research from the authors. The reason for this is not apparent but potentially the prohibitive manufacturing complexity of directing hundreds of fibre optic cables from the device to the target or higher losses than were theoretically predicted. Later work from the same authors [98] investigated the light leakage from fibre optics with a broadband spectrum. This research reported that the leakage is more significant than the ideal values suggested by the manufacturers due to imperfect total internal reflection, among other considerations. This is likely to be a

contributing factor to the lack of development of this device.

Fig. 2.28b shows a concentrator which is used for photonic surgery and was also developed by Feuermann and co-workers [99]. The device employs an arc lamp with axisymmetric optics to direct radiation into a 1 mm diameter fibre optic cable. A spherical light recycling mirror is also employed to increase the brightness of the source and improve the efficiency of the setup via light recycling. The authors noted in a previous paper on the same topic that coherence or monochromaticity is not required for this application, and therefore, lower-cost alternatives to lasers should be investigated [100]. The maximum power deliverable using the device was not specified, but between 1.7 W and 2.3 W were experimentally tested (220 - 290 W/cm²). This feat is made possible by the small extent of the arc, which allows the emitted radiation to be treated as a point source. This feat will be considerably more difficult with a larger extent QTH source.

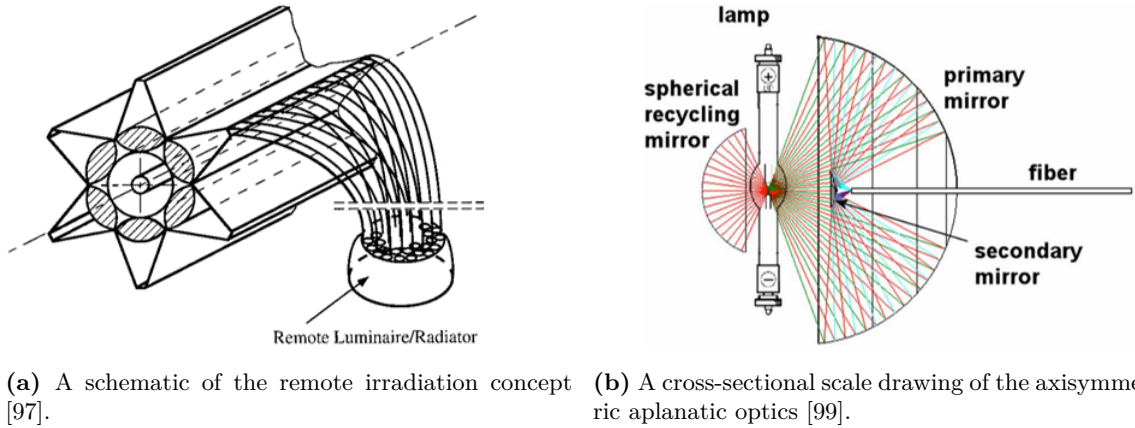


Figure 2.28: Nonimaging optic design examples.

The concepts developed in NIO are beneficial for the understanding of the theoretical limits imposed on a device that transfers radiation from a source to a target. However, the tools used to design NIO are restricted to quite simple geometries and do not holistically take into account the complexity required to model this problem with sufficient accuracy (e.g. the effect of the quartz envelope, absorbing-emitting media, varying reflective properties of the surface) [101]. If the filament and quartz envelope were a more suitable geometry (spherical, for example) and only a single reflection of radiation was expected, these techniques would be more appropriate, but since this is not the case, alternative design approaches require exploration.

2.5.4 Illumination design

Related to NIO is the field of illumination design. This field of research deals with the manipulation of light in order to suit a specified beam distribution for a given application, e.g. vehicle headlights, projectors, and street luminaries. Rather than maximise heat flux over a target surface, the goal of illumination design is to transfer luminous flux from a source to a distant target with a specified distribution. Despite the difference in objective, the techniques and concepts employed in this field are highly relevant to the topic of this research.

Much of the pioneering work on reflector design for illumination is attributed to Jolly, Waldram and Wilson in the book entitled “The theory and design of illuminating engineering equipment” published in 1931 [102]. Due to its age, this work is difficult to obtain in its original form, but the main contributions have been summarised by Falicoff [103]. The reflector design methods developed by *Jolly et al.* included solutions to specular, diffuse, and mixed reflectors for point sources. Solutions to axisymmetric reflectors were also attempted with reasonable success given that these were the formative years of this field, and graphical methods were used in the absence of computing capability. These approaches formed the foundation for many of the design methodologies that followed.

Since the early work of Jolly and others, there has been a great deal of research carried out in this area. Contending with extended sources is one major challenge which increases the complexity of obtaining a desired distribution on the target. One solution is to create an initial design by assuming a point source and manually adjusting or “tailoring” the shape until the required distribution is delivered [104]. A more rigorous method is to use edge-ray design principles [105, 106] to generate the initial shape for the extended source. However, in many cases, the manual adjustment may still be required after the generation of the initial design. Unfortunately, this entire process is slow and is heavily reliant on the experience of the designer.

In 1994 when describing the difficulty of designing using these manual “trial-and-error” strategies, Ashdown [107] recommended iterative optimisation routines coupled with RT for the design of nonimaging optical devices such as lenses, reflectors and luminaries. Since then, various illumination design strategies using iterative approaches have been reported with improved results such as the work of *Fournier et al.* [108], *Rabl et al.* [109] and *Mas et al.* [110]. The use of optimisation routines became prevalent in recent decades due to the

increase in computing power and the benefits brought by these techniques. There are many types of optimisation routines used throughout this field and other related fields which are briefly discussed in the following section.

2.5.5 Optimisation routines

The particular optimisation routine recommended by Ashdown was a *genetic algorithm* (GA), which is an optimisation approach that is based on the Darwinian evolutionary theory of natural selection or “the survival of the fittest” [111]. This method initialises with a random population of starting points (typically between 10 and 100 candidate solutions) which provide broad coverage of the multidimensional solution space. Each data point is evaluated for fitness based on an objective function, and after which, the proceeding generation is created through mutation and crossover of selected candidates. GAs are robust, meaning that they are very likely to arrive at a solution which is close to the global optimum for a range of challenging problems and also do not require any prior information about the search space. GAs are inherently parallelisable since each of the solutions can be enumerated independently, which is a distinguishing feature given the prevalence of multicore processors. Even still, these routines are typically more computationally expensive than more specialised search algorithms. A detailed description of the operation of GAs can be found in the work of Mitchell [112].

Particle swarm optimisation (PSO) is a solution space search method which is similar in many respects to a GA. This search algorithm optimises a problem based on the concept of swarm intelligence, which is often observed in social biology (such as with ants, bees, and birds). PSO was introduced by Kennedy and Eberhard in the 1995 paper entitled “A new optimiser using particle swarm theory” [113]. Randomly located solutions in the search space (referred to as particles) are seeded, and their fitness value enumerated. Similar to a GA, the final solution can be sensitive to the starting position so multiple optimisation processes may be required to verify repeatability. Based on the results of the first iteration, the velocity and position of the particle will be updated using a tuneable formulation, and the particles will begin to move around the solution space towards an optimum.

GAs, PSOs, and other similar strategies are often referred to as “metaheuristic” optimisation strategies. This term describes optimisation routines that “sample” a solution space which is too large to perform a brute force search. Metaheuristics do not rely on the differentiation of the objective function (in contrast to gradient-based solvers) but instead, use

search rules to traverse the search space and converge on optimal solutions. Metaheuristic techniques were also suggested by *Porter et al.* [114] and *Mas et al.* [115] for shape-based optimisation problems to overcome the limitations of other strategies such as nonlinear programming and gradient-based solvers. An example of the advantages of a metaheuristic technique over a gradient-based method is shown in Fig. 2.29, where the metaheuristic technique's movement around the search domain is less restricted and can even allow transition to an inferior solution. Metaheuristics, like most optimisation processes, do not guarantee convergence on a global optimum, but if tuned correctly, will often find a solution which is acceptably close to the optimum in the context of a complex search space and limited computing power.

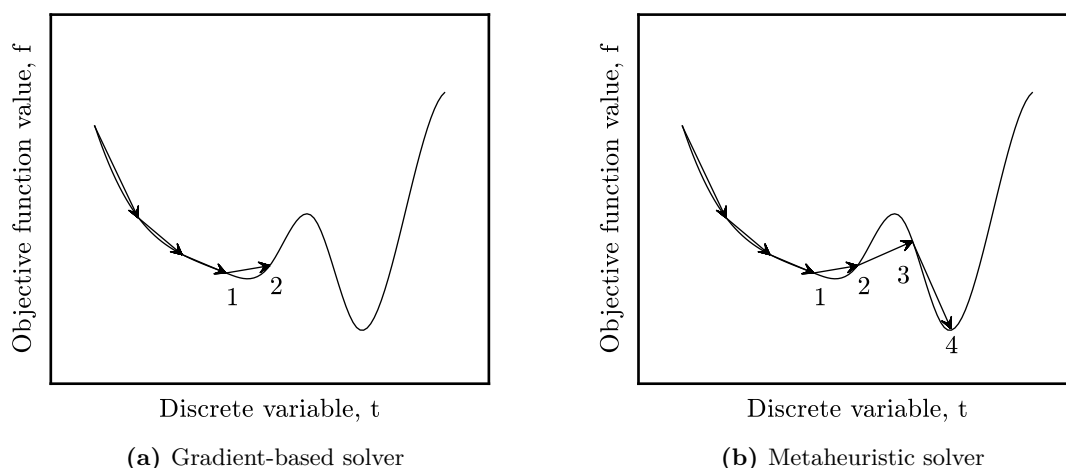


Figure 2.29: Comparison of two common optimisation strategies. Adapted from [114].

Other algorithms of the metaheuristic class include simulated annealing and tabu search. *Simulated annealing* is a probabilistic search method, which is analogous to the annealing of metals [116]. This technique initiates at a high “temperature” which controls the probability of moving to better and worse candidate solutions. This is comparable to the number of states that can be occupied by a metallic microstructure which gradually decreases as the temperature of the material reduces. As the temperature of the process is decreased in simulated annealing, at each decision point, the probability of moving to a higher state is increased, and the probability of moving to a lower state reduced.

Tabu search is an adaptive memory optimiser which allows the searching of wide solution spaces with many local extrema, such as scheduling and space planning [117]. The premise of this technique is a unique memory structure referred to as a “Tabu list” which stores the

positions in the solution space that should not be searched again. The Tabu Search uses a random or specified seed point and then searches the solution value of its nearest neighbours. After the evaluation of one or some of the neighbouring solutions, some may be added to the Tabu list depending on the exact formulation of the algorithm. The results of the work by *Porter et al.* [114] show that both metaheuristics techniques are viable for the optimisation of radiation-based problems, but that tabu search performs better in terms of the delivered solution and with a shorter time required to reach that solution.

2.5.6 Iterative illumination and solar design

Despite the recommendation of Ashdown [107] to use RT and GAs for illumination and NIO design, there are limited examples of the implementation of these two techniques. This is likely due to the prohibitive computational costs associated with simulating many thousands or even hundreds of thousands of rays. For example, Stock [118] investigated the automated design of illumination reflectors using a range of methods, and although RT was the preferred fitness evaluation approach, the difficulty in calculating ray-surface intersections and the limited computational power available at the time meant it was not possible. However, in one case, *Doyle et al.* [119] utilised a GA and RT to automate mirror design for luminaire based applications with promising results, albeit with a straightforward source representation and no participating media.

Moving on to other implementations, *Yang et al.* [120] investigated the automated design of custom reflectors using differential evolution and MCRT for both the case of illumination and concentration using an open reflector. Differential evolution is a less well-known variant of a GA which uses different mutation, selection, and recombination functions. The feasibility of using this combination of techniques was demonstrated with the process able to find close to the optimum for both tasks investigated.

Solar based applications have received enormous attention in recent years with the push towards renewable energy sources. This has led to the optimisation of various components such as solar troughs, mirrors, and Fresnel lenses. *Cheng et al.* [121] optimised a parabolic solar collector through using a MCRT and PSO combination. The objective was to maximise the collection efficiency of the solar collector, which was achieved through the optimisation of the aperture width and focal length. The problem tackled by *Cheng et al.* was quite simple with only two design variables, but particle swarm has also been used in more complex problem sets including other solar applications and heat transfer problems [71, 122].

In 2013, MCRT was employed by Mecit to investigate a concentrated solar power system [123]. This setup used a heliostat to concentrate solar radiation onto a gas-particle suspension which volumetrically absorbs the incident radiation. The heated gas could then be subsequently used for power generation. A schematic of the setup is shown in Fig. 2.30. This is a challenging problem which requires the transmission of solar radiation through a quartz window, taking into account the diffraction, reflection, and absorption properties of the quartz. This is exacerbated by the fact that these properties are strongly dependent on the wavelength of the radiation. Therefore, this problem cannot be assumed grey, like many problems discussed so far. The challenge was approached through simulation of the solar wavelength distribution using a large number of rays and assigning each ray a wavelength based on a cumulative distribution function. The material properties for each ray can be then assigned based on the wavelength of the ray. The result demonstrated that the MCRT method could calculate the overall transmission, absorption, and reflection losses of the various windows tested and thus was a suitable choice for this problem type.

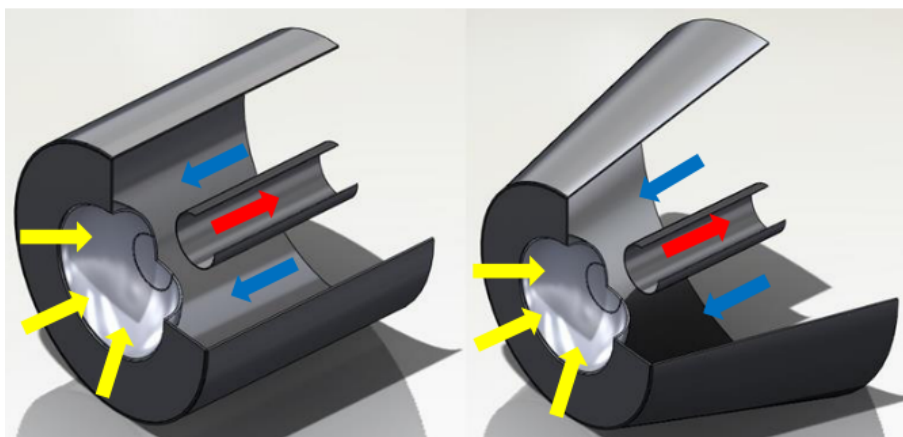


Figure 2.30: Schematic of the Small Particle Solar Receivers modelled by *Mecit et al.* [124] using the MCRT technique (yellow arrows: solar irradiation, blue arrows: air-particle mixture inlet, red arrows: air-particle mixture outlet).

2.5.7 Radiation enclosures

The design of radiation enclosures is another field which is closely related to that of a FIRH. A radiation enclosure employs a heat source or combination of sources to direct radiation towards the design surface with the desired distribution, as depicted in Fig. 2.31. The heat source is typically either another wall in the enclosure, an embedded heater, or an incandescent lamp. The optimisation of the radiation enclosure involves modifying the geometric shape of the enclosure, the position of the heat source(s) or power applied to

individual heat sources to reach the specified heat flux distribution on the design surface. Similar to the design of many mechanical, thermal, and optical systems, trial-and-error based design techniques were employed in the formative years of this field, although more recently, optimisation routines have come to the fore.

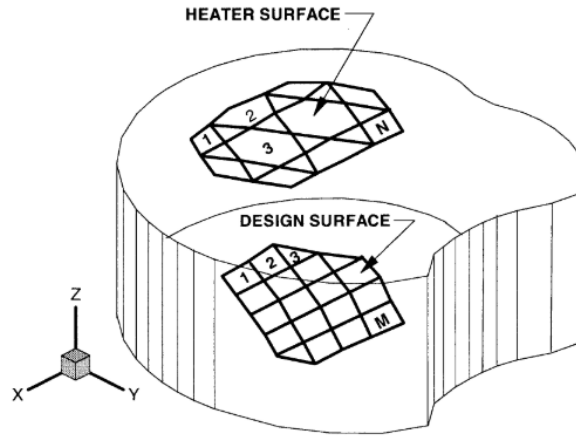


Figure 2.31: Radiation enclosure optimisation [125].

One of the first radiation enclosure optimisation problems documented in the literature was tackled using a process developed by *Fedorov et al.* [126] who inversely optimised a conveyor based IR heating process. This analytical model required taking into account radiative, convective, and conductive heat transfer within the target material that was moving through a six-walled cuboid enclosure. The model assumed secondary reflections were negligible, diffuse surfaces, and that the material properties partitioned into a finite number of wavelength bands. Later, *Daun et al.* [127] employed an infinitesimal area analysis technique to find the optimal shape of a four-walled 2D enclosure. Again, reflections were assumed diffuse. The speed of optimisation was a major benefit delivered by this method with total run times of less than a minute. The rapid optimisation was achieved using a gradient-based solver which will likely not translate to the optimisation of more complicated geometries. In the same year, *Daun et al.* [128] also employed a MC method to determine exchange factors between surfaces by assigning a position and direction to a ray based on random number generation. This negated the need for the diffuse assumption and allowed specular surfaces to be optimised.

Sarvari [86] optimised a radiation enclosure using the discrete transfer radiation method for a problem with transparent media. The discrete transfer radiation method is a modelling

technique which allows the evaluation of the heat flux on the radiation enclosure's surfaces by discretising the surfaces into individual elements and then using the midpoint of these elements to define the divisions in the solid angle of emission. It was assumed that the walls were diffuse-grey. This technique successfully generated a uniform heat flux over the design surface with a small margin of error. Specular radiation enclosures were also investigated using a quasi-MC method by *Martson et al.* [129] in 2011. This work followed on from the use of the MC method with specular solar collectors in the year previous [101] and the initial development of this model for specular radiation enclosures outlined by *Daun et al.* [128]. Given the work discussed in the literature surrounding radiation enclosures, it is clear that the MC method is the only suitable technique for the modelling of this problem type where specular reflections with nongrey surfaces are necessary.

The use of optimisation algorithms in radiation enclosures is mixed. *Daun et al.* [127, 128] prefer the Kiefer–Wolfowitz algorithm, as this method can combat the statistical noise inherent to the MC technique. Although a major drawback of this algorithm is that it is a gradient-based solver that may optimise to local extrema and fail to find global optimums for complex solution domains. Sarvari [86] employed a GA with promising results which was later followed on by *Farahmand et al.* [130] but this time using the PSO method. It was reported that the PSO method delivered improved results when compared to the GA but with longer computation times. As discussed previously, variations of GAs [120] and the PSO algorithm [121] have also been used with MCRT shape-based problems successfully, and therefore metaheuristic optimisation processes are deemed to be a judicious choice. It is unclear which of these algorithms is most suitable for this particular problem type, but given the proven track record of the use of the GAs in heat transfer [131], shape optimisation [119], and design [132], this algorithm is selected for use going forward in this work.

2.6 Defining a shape parametrically

Parametrically defining a shape is a critical part of the overall optimisation process that has yet to be addressed in this review so far. When deciding on a shape parameterisation technique, Keane and Song [133] describe the need for a balance between robustness and flexibility so that there is sufficient freedom to generate a range of shapes, yet not so much freedom that the stability and robustness of the curve are compromised. The number of input variables is also important with a more compact representation suitable for use as

input into a shape optimisation algorithm.

Splines are smooth tractable curves which are defined using a small number of points. This parametrisation technique has been widely used in the literature discussed so far [86, 101, 120, 129, 134, 135]. Much of the relevant shape parametrisation literature arose from development in the aeronautical industry where various techniques were used to model the shapes of aerofoils. A comprehensive review of the different methods currently in use today for aerofoils is provided by *Zhang et al.* [136].

The broad term of B-splines or basis spline is used to describe curves of varying degrees whose shape is modified by changing the position of control points. These control point coordinates can be input into a shape optimisation program to allow various geometric shapes to be represented. An example of five-point B-splines of varying degrees is shown in Fig. 2.32a with the Bézier curve shown as a curve of degree four. Any B-spline with one degree less than the number of control points is considered a Bézier curve as this means that there are no internal joints or “knots” required. For lower degree curves to create the shapes shown in Fig. 2.32a, the joining of multiple curves is necessary, which increase the complexity of the parametrisation. Bézier curves are, therefore, the simplest form of a B-spline. One drawback of a Bézier curve is that the curve cannot be controlled locally — any modification to a control point will result in a change to the entire curve, although changes far away from the control point will be relatively small.

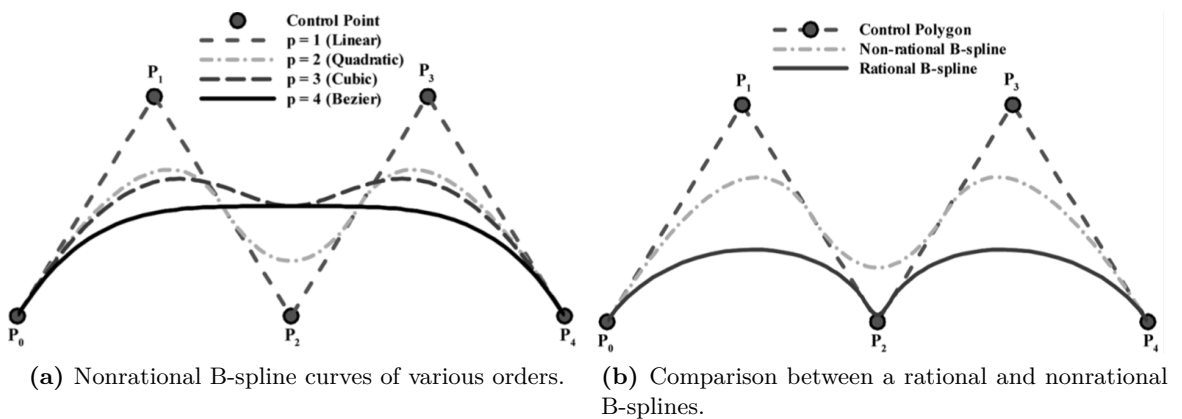


Figure 2.32: Schematic of various shape parametrisation splines [86].

Splines can also be rational or nonrational, as shown in Fig. 2.32b. For example, NURBS is a B-spline for which the control points can be weighted. Although this provides higher degrees of freedom, there is also additional variables to manage when performing the opti-

misation process. Given that the shape required for a FIRH need only be concave, complex nonrational representations are not required, and as such, the Bézier curve will be employed for this work.

2.7 Summary and research objective

This review introduced IR heating technology, the subset of this field known as focused IR heating, and the range of applications where this technology is employed. There are still many aspects which remain unexplored despite the potential of this technology to be used across many areas of research and industry. In particular, the design strategies employed in the development of FIRHs are primitive and involve the use of restrictive reflector shapes which are not bespoke to the source employed.

The topic of heat transfer was first familiarised as a field which is fundamental to the operation of FIRHs. Subsequently, the IR source type which will be used in this investigation was introduced and the physics underlying its operation explained. The majority of the heat emitted from this source will be transported by radiation; however, the exact percentage of the total power input that will be emitted by radiation is unknown. Very little fundamental research has been carried out on these lamps, and hence the thermal performance of QTH sources or the effect of operating conditions on the performance of these lamps is not yet understood.

Attention was drawn to the commercially available FIRHs and concluded that these devices are large in scale and inefficient in terms of radiative performance. These devices employ elliptical reflectors which are designed with the supposition of a point or minimally sized source, which is not the case for commercial high powered QTH sources. Improved performance can be obtained by developing a custom shape which is tailored for the lamp and filament geometry.

The concept of light recycling was introduced, and it was explained how this had been previously used to improve the radiance of sources by up to 30%. Further enhancements are anticipated with an enclosed double-coil filament. Light recycling will be a key design feature that may allow improved performance of the FIRH by returning radiation which does not exit the reflector back to the filament, enhancing the brightness of the source.

Although on first appearance, nonimaging optics and illumination design would seem to be very similar to the task being addressed in this work, there are several relevant differences.

Firstly, many of the methods employed in these fields only take account of one reflection of a ray, have restrictive assumptions such as grey or diffuse surface properties, or ignore surface properties entirely. Moreover, techniques such as the edge ray theorem cannot take into account the effect of the quartz envelope where absorption and refraction of radiation will have a significant impact on the distribution emitted from the lamp. Radiation enclosure design presents a range of techniques for modelling radiation in confined reflective bodies. The MCRT method is preferred where simplifying assumptions such as grey and diffuse surface characteristics cannot be applied.

Concerning the optimisation of the reflectors, various techniques were reviewed from the literature. Gradient-based solvers are not suitable for the problem at hand given the number of dimensions which will need to be searched and the likelihood of these algorithms settling in local optimums. GAs, PSO and other metaheuristic algorithms were found to be the most suitable for multidimensional problems. A GA was selected based on this algorithm's ability to optimise a wide range of problems, including radiative heat transfer based problems. Bézier curves were found to be a robust yet straightforward shape parameterisation technique, and thus will be employed along with the GA and MCRT techniques to complete the optomechanical design process.

There exists a gap in the literature concerning the design and optimisation of custom reflector shapes for focused IR based applications. Therefore in this context, the primary objective of this research is as follows:

Develop a design methodology to optimise FIRHs that can deliver improved performance using a smaller reflector geometry when compared with those which are presently available on the commercial market.

Consequently, several secondary objectives arise following from this primary objective:

1. Characterise the IR source used in this investigation and determine the ratio of radiative power output to the total power input (i.e. the radiative efficiency) for a range of suitable operating conditions. This work will provide the foundation for the successive chapters where the source tested will be modelled and then used in a manufactured FIRH.
2. Develop a comprehensive computational model which employs MCRT, a GA, and a Bézier curve as the framework to allow for the optimisation of custom reflector shapes. This model should be able to perform computations in a time-efficient manner to allow

the testing of the vast number of shapes prescribed by the GA.

3. Design and manufacture a FIRH which delivers improved performance in comparison to commercially available devices. The device should be adequately characterised to validate the numerical model and ensure that the device is suitable for use in a range of applications.
4. Determine the effect of light recycling of the IR source on the performance of a FIRH. Estimate theoretical limits for the focused IR technology based on this principle.
5. Finally, characterise the trade-off between efficiency and heat flux with a change in outlet size for a FIRH with given source type. Based on this trade-off, establish design principles and strategies to allow a FIRH to be designed for a particular application.

A summary of these tasks and related outputs are provided in Fig. 2.33. The development of the MCRT model will be performed in two steps, with a simplified 2D model first established to validate the optimisation procedure, and later progressing to a full 3D model representation.

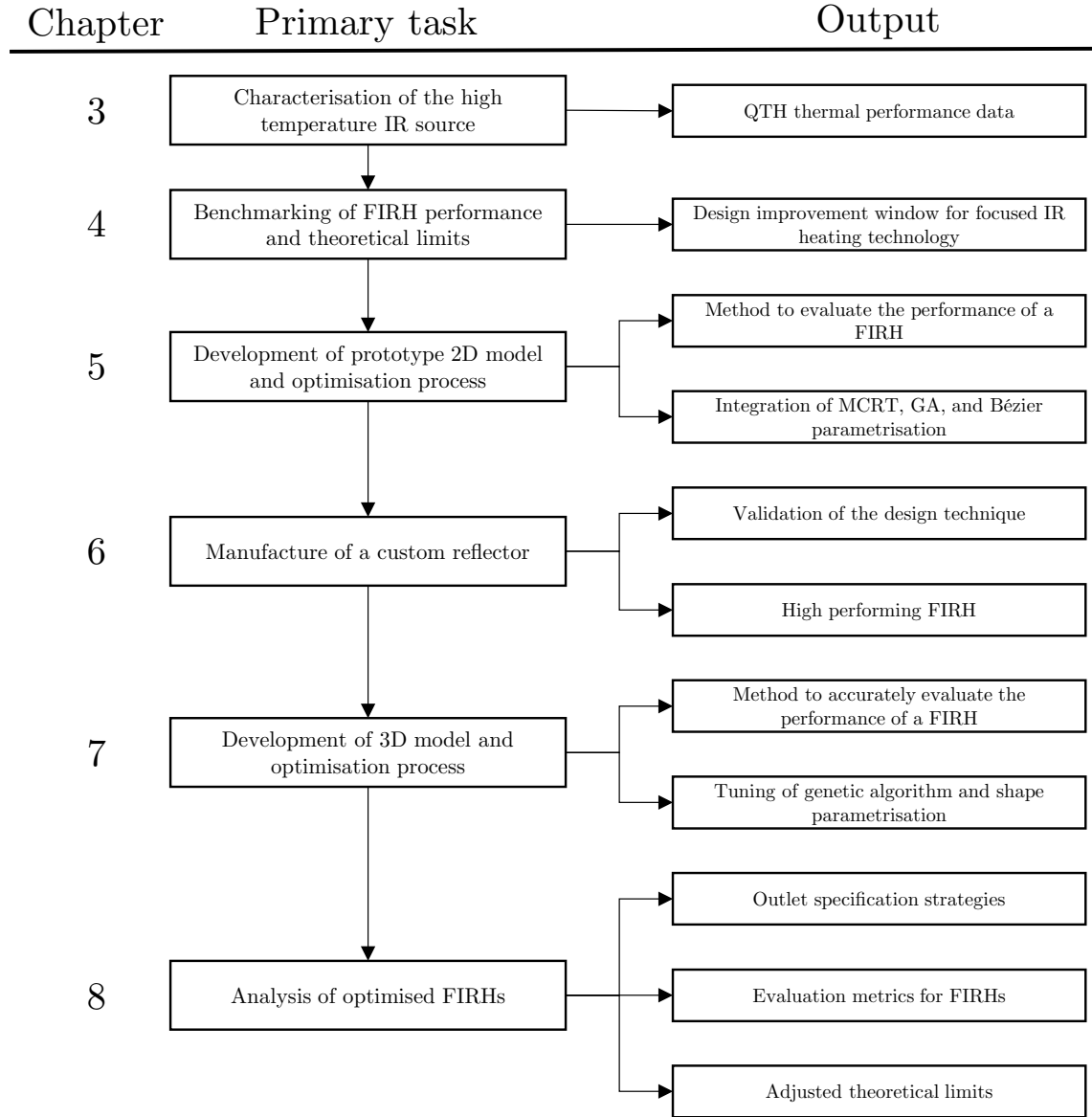


Figure 2.33: A summary of the primary tasks to be undertaken in this work.

Chapter 3

Energy Efficiency of a Quartz Tungsten Halogen Lamp

3.1 Introduction

As discussed in section 2.3.1, there is an evident lack of research dedicated to the thermal performance of QTH sources. Since the design of a radiant heating system or any system which employs a QTH lamp, at the very least warrants an estimate for radiant heat emitted from the lamp, this chapter aims to contribute to the understanding of these IR heat sources by comprehensively studying a single QTH lamp over a range of filament operating temperatures. First, a more detailed review is provided of the research carried out surrounding QTH lamps to date.

Early research into the experimental validation of heat transfer models of QTH lamp based systems assumed that losses due to convection and conduction were negligible and that the lamps converted 100% of the electrical power input to radiation [51]. Several more recent studies also made a similar assumption [137–139]. Conversely, Pettersson & Stenström [36] used an in-house transient model to predict radiative efficiencies in the range of 55% at low power and 86% at high power for a double-ended QTH lamp, although the efficiency was not experimentally validated. The balance of power was accounted for in the model by conductive losses from the filament to the quartz envelope and subsequent convection to the atmospheric air. The research concluded that at low power input, the modelled IR lamp was not an efficient radiator. Additionally, in the work of *Lee et al.* [56], the manufacturer of the QTH lamps used in the work specified that the electrical-radiative efficiency was 85%; however, neither dependencies on voltage input nor the technique used to obtain this value

were indicated. Bedard [35] carried out a detailed characterisation of electric and gas powered IR heaters with regard to planar radiant heat flux mapping, radiant efficiency and spectral emission. An array of 13 Schmidt-Boelter heat flux gauges were employed to measure the 2D planar radiative power output, which allowed the radiative efficiency to be estimated. Bedard reported that the radiant efficiency of the IR sources varied between 36% and 90% and strongly depended on the type of heater used. Compared to the gas-fired IR sources, the two QTH lamps delivered higher efficiencies of between 74% and 83% when tested at a constant input of 420 V. However, the efficiencies were only measured at a single voltage level, and hence the effect of voltage input or filament temperature on the efficiency was not considered.

Brown et al. [140] used a spherical heat flux mapping technique to determine the electrical-radiant efficiency of ceramic space heaters over a range of input powers. The total heat flux output of the heater was measured using a Schmidt-Boelter heat flux gauge and a precisely controlled 6-axis robot arm which was then compared to the power input to allow the radiative efficiency to be found.

Given the experimental data at a single voltage level from the work of Bedard [35] and the model predictions by Pettersson & Stenström [36], it is apparent that it is erroneous to assume that QTH lamps convert electric input to thermal radiation at 100% efficiency. However, aside from the aforementioned studies, no data is available from which to estimate the efficiency of a given QTH system. Therefore, this chapter will study a single QTH lamp over a range of filament temperatures using a heat flux mapping technique similar to that employed by *Brown et al.* [140]. The development of a numerical model in ANSYS Fluent which can predict the radiative performance of these IR sources and provide insight into the operation of these sources will also be detailed and discussed.

3.2 Experimental methodology

3.2.1 Experimental setup

The IR source used in this investigation is a single-ended GE Lighting CP77 1000 W FEP which operates at a maximum of 230 V with a rated life of 300 hours. This lamp was selected for characterisation as the source was utilised successfully in previous studies [53, 137] and employed as the source for a FIRH in the previous work of the author [10]. An SBG01-50 radiant heat flux sensor (Hukseflux, Netherlands) was employed to measure the heat flux intensity of the lamp which was calibrated between 0.5-5 W/cm² by RISE (Research Institute of Sweden AB) according to ISO 14934-2 and ISO 14934-3 [141]. This heat flux sensor is delivered with a carbon black absorbing coating which has a flat spectrum from 0.2 to 50 μm and thus is suitable for the measurement of broadband IR sources. The sensor outputs a voltage of 0-16 mV depending on the level of incident radiation, which was measured using a low voltage DAQ (NI 9213). The data was collected using LABVIEW and post-processed in MATLAB 2017a to determine the corresponding heat flux level, create the heat flux maps, and calculate the electrical-radiative efficiency of the lamp. The positioning of the lamp was achieved using a CNC controlled chuck and spindle. Power to the IR lamp was delivered using an Elektro-Automatik PS 8360-10T DC power supply with an associated uncertainty of 0.2% for the voltage and current outputs. A schematic of the experimental setup is shown in Fig. 3.1a, along with an illustration of the heat flux mapping technique in Fig. 3.1b.

3.2.2 Radiative efficiency and spherical heat flux mapping

To determine the heat flux output distribution and radiative efficiency of the IR source, a heat flux sensor must measure the heat flux output on the surface of a sphere which encapsulates the lamp. Previous work in the literature achieved this using a 6-axis robot arm where the sensor was rotated around a stationary heat source [140]. In this investigation, the heat source was rotated while the sensor was fixed in position below the source, which negated the need for a complex positioning system. This also implies that the sensor never entered the rising plume of heated air and that the experimental setup matched the calibration setup (where cool, stagnant air surrounds the horizontal sensor surface); therefore convective influences on the heat flux measurement are accounted for by the calibration. A custom set of holding jigs were manufactured to ensure that the lamp was positioned accurately and could be rotated about the filament's geometric centre at the required angles.

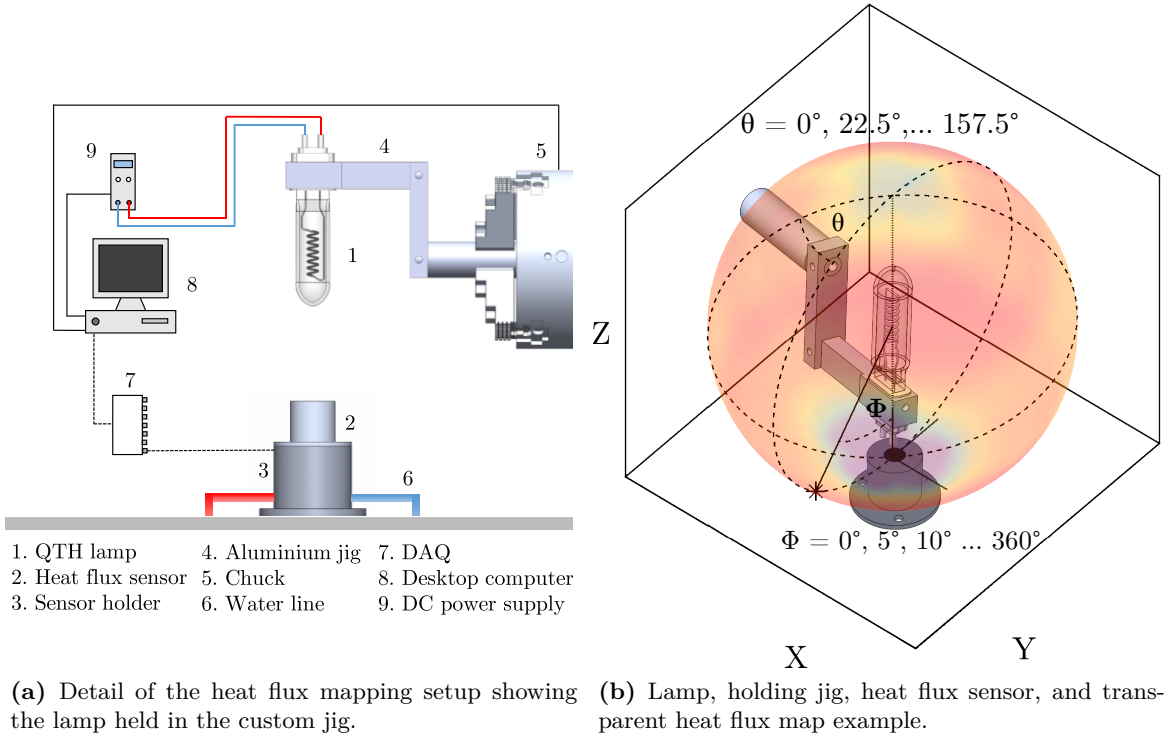


Figure 3.1: Experimental setup for characterisation of the QTH lamp.

The sensor body was maintained at a distance of 78 mm from the geometric centre of the filament, and the sensing surface was located 0.3 mm below this surface, providing a total radius of 78.3 mm. The lamp was rotated from 0 to 360° in steps of 5° for a total of 72 measurement points using the chuck and spindle. This was repeated after rotation about its Z axis from 0 to 157.5° in steps of 22.5° using the custom holding jigs. Since there is significant variation in the heat flux level longitudinally from pole to pole on the measurement sphere, an angle of 5° was chosen to provide an arc length which is less than that of the sensing element diameter. The lateral variations in heat flux levels are much smaller, and therefore, a larger step size can be used. The overall process and angle convention used is illustrated in Fig. 3.1b with an example heat flux map. This procedure was repeated in steps of 10 V starting at 140 V up to the maximum voltage of 230 V. Lower voltage tests were not performed as the measured heat flux levels would have fallen outside of the calibration range and compromised the accuracy of the radiative efficiency measurement.

The radiant power output through the spherical surface was determined by assuming that the heat flux is uniform for each grid surface element so that the power through that element can be calculated by the product of the local heat flux q''_{ij} and the surface area of the element A''_{ij} . This allows a numerical integration to be performed on the spherical

surface and the net radiative power output to be found by the addition of the elemental powers [140]:

$$P_{rad} = \sum_{i=1}^N \sum_{j=1}^N q''_{ij} A''_{ij} \quad (3.1)$$

The elemental surface areas were calculated as spherical surface elements with φ arc angles of 5° and θ arc angle of 22.5° such that the total area of the elements ($\sum_{i=1}^N \sum_{j=1}^N A''_{ij}$) is equivalent to $4\pi R^2$. The electrical power input was measured as a product of the voltage and current:

$$P_{elec} = V \times I \quad (3.2)$$

Finally, the total electrical-radiative efficiency of the QTH source was then determined by division of the radiative power by the electrical power input:

$$\eta_{QTH} = \frac{P_{rad}}{P_{elec}} \quad (3.3)$$

3.2.3 Lamp and filament analysis

The resistance of the lamp was measured as 3.56Ω at a temperature of 21.7°C with a digital multimeter (Metrix MX 22) using the average of 5 lamps soldered in series. The length to area ratio $\frac{L_{fil}}{A_{fil}}$ can be determined by a rearrangement of Eq. 3.4 using the calculated value of lamp resistance and the resistivity of tungsten:

$$R_{fil} = r_{tung} \times \left(\frac{L_{fil}}{A_{fil}} \right) \quad (3.4)$$

where R_{fil} is the ratio between the voltage and current level applied to the lamp ($R_{fil} = V/I$) and r_{tung} is the resistivity of the tungsten which can be determined using the correlation employed by *Logerais et. al* [142]:

$$r_{tung} = 5.92 \times 10^{-11} T_{fil}^{1.2036} \quad (3.5)$$

The $\frac{L_{fil}}{A_{fil}}$ ratio for this lamp was calculated to be $6.41 \times 10^7 \text{ m}^{-1}$. Using this value, the average temperature of the filament at each voltage operating point can be calculated using the following equation:

$$T_{fil} = \sqrt[1.2036]{\left(\frac{L_{fil}}{A_{fil}} \right) \times \frac{V/I}{5.92 \times 10^{-11}}} \quad (3.6)$$

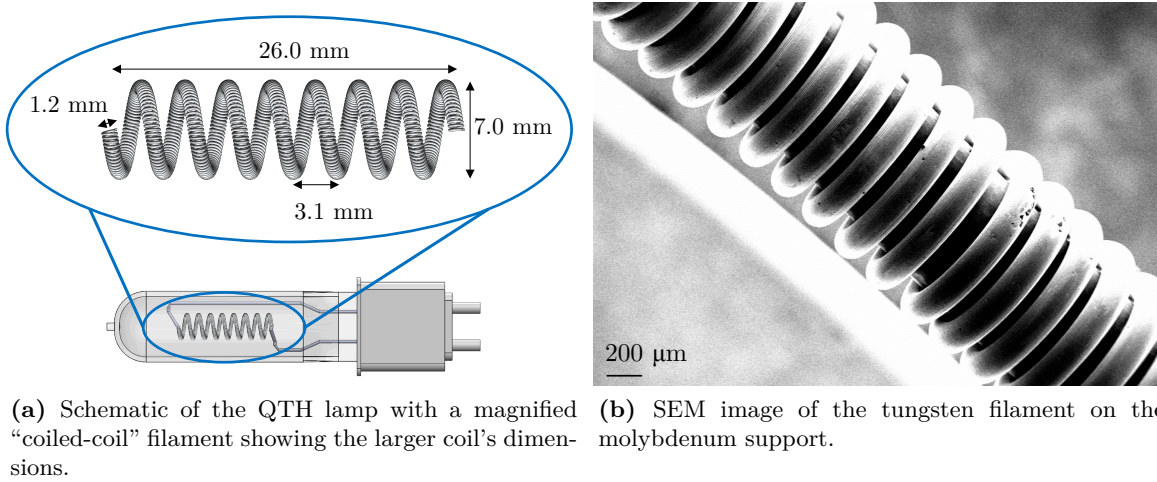
The experimentally calculated temperatures of the filament for each voltage level tested are

Table 3.1: Filament resistance and temperature for various voltage and inputs

Input Voltage (Volts)	Input Current (Amps)	Input Power (W)	$R_{Filament}$ (ohms)	$T_{Filament}$ (K)
140	3.05	426.3	46.0	2470
150	3.17	474.9	47.4	2532
160	3.28	525.2	48.7	2593
170	3.40	577.8	50.0	2649
180	3.51	631.4	51.3	2706
190	3.62	687.1	52.5	2760
200	3.72	744.0	53.8	2813
210	3.82	801.7	55.0	2867
220	3.92	862.1	56.1	2916
230	4.02	925.2	57.2	2961

provided in Table 3.1.

The filament dimensions are provided in Fig. 3.2a and a scanning electron microscope (SEM) image (Carl Zeiss ULTRA, Germany) of the filament on the molybdenum support is shown in Fig. 3.2b. The filament is characterised by thin tungsten wire which is coiled with a diameter of ~ 1.2 mm. This structure is then coiled again to form a “coiled-coil” with an outer diameter of ~ 7 mm.

**Figure 3.2:** The QTH lamp investigated in this work.

To determine the surface area of the filament, an equation for the diameter of the filament must be developed. This can be achieved using a measurement of the $\frac{L_{fil}}{A_{fil}}$ ratio (as described in section 3.2.3), the mass of the filament and the density of the tungsten, all of which can be measured or are known to quite a high degree of accuracy. Firstly, the length of the filament

can be evaluated using the product of the cross-sectional area of the filament (in terms of the filament diameter) and $\frac{L_{fil}}{A_{fil}}$ ratio assuming a cylindrical cross-section:

$$L_{fil} = A_{fil} \left(\frac{L_{fil}}{A_{fil}} \right) = \left(\pi \times \frac{D_{fil}^2}{4} \right) \left(\frac{L_{fil}}{A_{fil}} \right) \quad (3.7)$$

The mass of the filament can be evaluated as the product of the density of tungsten and the volume of the filament:

$$m_{fil} = \rho_{tung} \times V_{fil} = \rho_{tung} \times \left(\pi \times \frac{D_{fil}^2}{4} \times L_{fil} \right) \quad (3.8)$$

Eq. 3.8 can then be rearranged to isolate the filament length:

$$L_{fil} = \frac{4 \times m_{fil}}{\rho_{tung} \times \pi \times D_{fil}^2} \quad (3.9)$$

Equating Eq. 3.7 and 3.9:

$$L_{fil} = \frac{\pi \times D_{fil}^2}{4} \left(\frac{L_{fil}}{A_{fil}} \right) = \frac{4 \times m_{fil}}{\rho_{tung} \times \pi \times D_{fil}^2} \quad (3.10)$$

The filament diameter can then be isolated and determined:

$$D_{fil} = \sqrt[4]{\frac{16 \times m_{fil}}{\rho_{tung} \times \pi^2 \times \left(\frac{L_{fil}}{A_{fil}} \right)}} = 180.77 \mu m \quad (3.11)$$

The filament diameter was also measured as $177 \pm 3 \mu m$ using an average of 10 SEM measurements; however, the accuracy of this method is significantly less than that determined using Eq. 3.11 due to the measurement error inherent to the SEM micrograph technique [143].

The length of the filament can then be found using the filament diameter:

$$L_{fil} = A_{fil} \left(\frac{L_{fil}}{A_{fil}} \right) = \left(\pi \times \frac{D_{fil}^2}{4} \right) \left(\frac{L_{fil}}{A_{fil}} \right) = 1.65 \text{ m} \quad (3.12)$$

Finally, the surface area of the filament is calculated to be:

$$S_{fil} = L_{fil} \times \pi \times D_{fil} = 9.34 \times 10^{-4} \text{ m}^2 \quad (3.13)$$

3.2.4 Experimental error analysis

The error associated with the heat flux sensor varies from $\pm 2.3\%$ to $\pm 1.3\%$ between 0.5 W/cm^2 and 5 W/cm^2 according to the calibration report provided by RISE. Since the experimental data collection was carried out immediately after calibration, drift is not considered to be a significant source of error. The uncertainty of the radius of the heat flux map is estimated to $\pm 0.5 \text{ mm}$, which results in a relative error of $\pm 1.3\%$ for the surface area given a radius of 78.3 mm . These relative uncertainties can be summated to find the maximum relative error of the radiative power output:

$$U_{rad} = \sqrt{\left(\frac{U_{calib}}{q}\right)^2 + \left(\frac{U_A}{A}\right)^2} = \pm 2.6\% \quad (3.14)$$

The uncertainty of the power input is much lower as the voltage and current are known to quite a high degree of accuracy of $\pm 0.2\%$ for each, resulting in a total uncertainty of $\pm 0.3\%$. The uncertainty associated with the radiative efficiency is then also determined to be at most $\pm 2.6\%$.

The error associated with the experimental temperature measurement of the filament can be quantified using a summation of the errors associated with the voltage and current measurement, the resistance measurement and the resistivity correlation. The error associated with the tungsten resistivity correlation is assumed less than $\pm 1\%$ across the entire range and the resistance measurement is estimated to be at most $\pm 0.15 \text{ } \Omega$:

$$U_{T,fil} = \sqrt{\left(\frac{U_{resistance}}{R}\right)^2 + \left(\frac{U_{correlation}}{C}\right)^2 + \left(\frac{U_V}{V}\right)^2 + \left(\frac{U_I}{I}\right)^2} = \pm 4.3\% \quad (3.15)$$

The calculation of the filament diameter is a function of the $\frac{L_{fil}}{A_{fil}}$ ratio (which is a function of the resistance measurement) and the mass of the filament for which the error is assumed to be less than $\pm 0.01 \text{ g}$. Therefore, the uncertainty associated with the filament diameter is:

$$U_{D,fil} = \frac{1}{4} \sqrt{\left(\frac{U_{resistance}}{R}\right)^2 + \left(\frac{U_M}{M}\right)^2} = \pm 0.8\% \quad (3.16)$$

However, this is assuming a constant cross-sectional area, a uniform temperature across the entire cross-section and length of the filament, and a smooth filament surface. Therefore, this measurement may be subject to errors that are not possible to quantify; however, this surface area calculation can still provide an acceptably accurate estimate from which to construct

the numerical model domain.

3.3 Numerical modelling methodology

3.3.1 Numerical model domain development

The heat transfer process was simulated in ANSYS Fluent version 19.2 using a 2D axisymmetric model. The simulation is characterised by two fluid domains of the internal fill gas and external air separated by a quartz envelope, as depicted in Fig. 3.3a. The base of the lamp and the aluminium holder jig are also included in the simulation as joined aluminium bodies. The large coil is composed of a smaller, tightly coiled structure which cannot be modelled with sufficient resolution due to the size of the tungsten wire ($D_{fil} = \sim 180 \mu\text{m}$). Therefore, the filament was simulated in the model as 8 evenly spaced circular elements placed at the intersect locations of the large coil with the simulation plane. This simplification assumes that the concave nature of the smaller coil does not have a significant impact on the efficiency and temperature of the filament. Furthermore, in the axisymmetric simulation, the filament coils are independent of one another, which neglects the effect of conduction along the length of the filament wire. This assumes that these simplifications do not have a significant impact on the performance of the lamp.

The diameter of the circular elements of the filament in the model (1.85 mm) is chosen such that the area is equivalent to the revolved area of $9.34 \times 10^{-4} \text{ m}^2$ as calculated in section 3.2.3. The filament centres are located 3.2 mm from the rotational axis and have a centre to centre spacing of 3.1 mm. The lamp base and holder are not axisymmetric and therefore were modelled as a circular cross-section with the same cross-sectional area as the rectangular profile. Both the fluids were assumed incompressible although density changes due to temperature variations are taken into account allowing buoyancy effects to cause motion of the fluid. Since this is an axisymmetric flow, gravity can only be set in the axial direction (either in the positive or negative direction as 9.81 m/s), and thus the entire experimental procedure cannot be reproduced. However, the efficiency and the temperature data presented in the results section are average values determined by taking into account both the gravity directions. The pressure at the inlet and outlet was set to 100 kPa absolute and 400 kPa absolute inside the quartz envelope, respectively. The flow regime inside and

outside the quartz envelope can be determined using the Rayleigh number [17]:

$$Ra = Gr \times Pr = \frac{g\beta(T_{hot} - T_{cold})X^3}{\nu\alpha} \quad (3.17)$$

The hot and cold temperatures were determined from the output of the numerical model while the characteristic length X was assumed to be the internal diameter of the quartz envelope and the height of the quartz envelope for the internal and external case, respectively. The transition from laminar to turbulent (considered to be $Ra_{crit} \approx 3 \times 10^5$ for enclosed heated plates and $Ra_{crit} \approx 10^9$ for a vertical cylinder or plate [16]) is orders of magnitude greater than the calculated values for the internal ($Ra \approx 10^2$) and external flow ($Ra \approx 10^6$). Therefore, simulation of the internal and external flows can safely be assumed laminar in the numerical model.

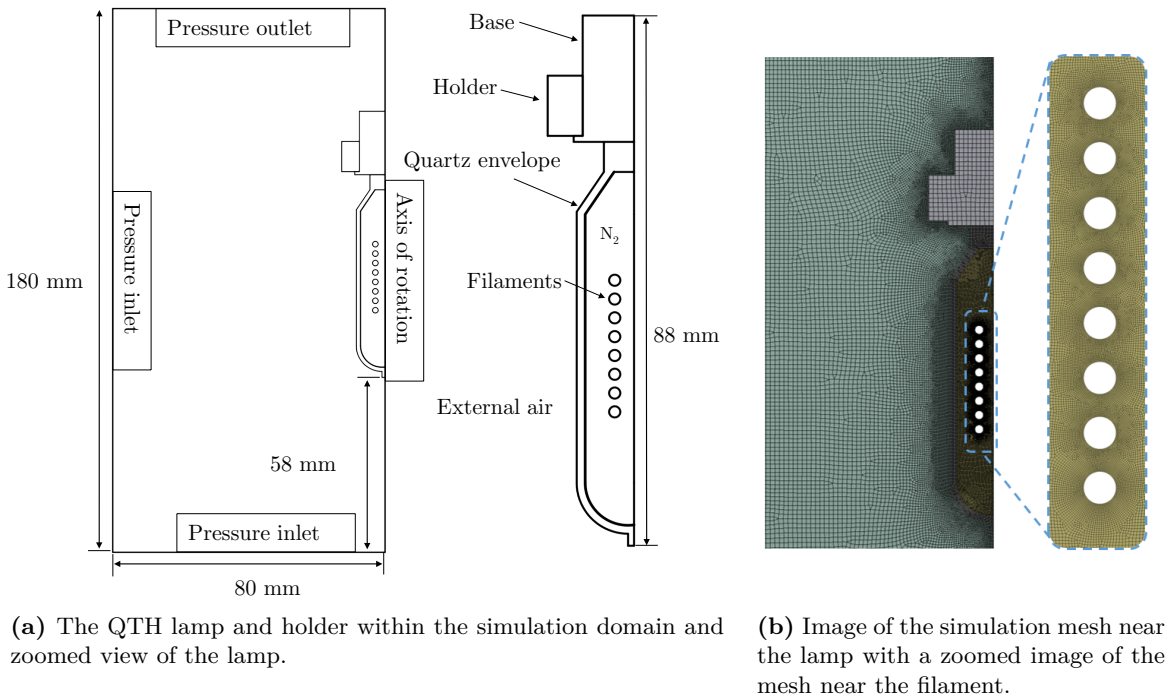


Figure 3.3: Illustration of the simulated QTH lamp.

For a steady, incompressible axisymmetric flow of a Newtonian fluid, the governing equations of continuity, radial and axial momentum are described in Eq. 3.18 to 3.20:

$$\nabla \cdot \mathbf{v} = \frac{1}{r} \frac{\partial(rV_r)}{\partial r} + \frac{\partial V_z}{\partial z} = 0 \quad (3.18)$$

$$\rho \left(\frac{\partial V_r^2}{\partial r} + \frac{\partial(V_r V_z)}{\partial z} \right) = -\frac{\partial P}{\partial r} + \mu \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V_r}{\partial r} \right) + \frac{\partial^2 V_r}{\partial z^2} - \frac{V_r}{r^2} \right) \quad (3.19)$$

$$\rho\left(\frac{\partial(V_r V_z)}{\partial r} + \frac{\partial V_z^2}{\partial z}\right) = -\frac{\partial P}{dz} + \mu\left(\frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial V_z}{\partial r}\right) + \frac{\partial^2 V_z}{\partial z^2}\right) - g(\rho - \rho_0) \quad (3.20)$$

Swirl at the inlet to the system is considered negligible and therefore, the angular momentum component can be neglected. The energy equation for an incompressible, laminar, steady flow is:

$$\rho C_p \left(\frac{1}{r} V_r \frac{\partial T}{\partial r} + V_z \frac{\partial T}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left(k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q_{radiation} \quad (3.21)$$

where ρ is the density, P the pressure, V_r and V_z are the radial and axial velocity components respectively, μ is the dynamic viscosity, C_p is the heat capacity, g is the gravitational constant, T is the temperature, and k is the thermal conductivity of the fluid. Radiation heat transfer in conjugate heat transfer problems is often solved using the surface to surface model [144], however, given the transparent quartz medium and varying material properties across the wavelength range of interest, the nongrey version of the discrete ordinates (DO) method must be used [145]. The problem is assumed to be steady-state, and with no scattering, for which the spectral intensity can be written as [25]:

$$\vec{s} \cdot \nabla I_\lambda(r, \vec{s}) + \kappa I_\lambda(r, \vec{s}) = \kappa I_{b\lambda}(r) \quad (3.22)$$

Where $\vec{s}$ is the direction vector at a location of r , λ is the wavelength, and κ is the spectral absorption coefficient. The blackbody emission for each of the wavebands, $I_{b\lambda}$, is defined as:

$$I_{b\lambda} = [F(0 \rightarrow n\lambda_2 T) - F(0 \rightarrow n\lambda_1 T)] n^2 \frac{\sigma T^4}{\pi} \quad (3.23)$$

Where λ_1 and λ_2 are the lower and upper wavelengths for a given band, and n is the refractive index of the medium.

3.3.2 Mesh development and numerical model settings

ANSYS Workbench was used to generate the mesh for the simulation, which is shown in Fig. 3.3b. A maximum element size of 1 mm was set in the external air region and of 0.2 mm in the internal fill gas region. Further refinements were applied around the filament surfaces using inflation layers. The mesh had a total of 64k nodes and 62k elements with an average quality of 0.93, minimum orthogonal quality of 0.86 and a maximum aspect ratio of 4.08. Before carrying out the final simulations, the mesh density was increased by approximately 70% and resulted in <0.2% change in the calculated efficiency and filament temperature.

The simulation proposed is therefore considered mesh independent.

The solver type was set to a pressure-based axisymmetric model under steady-state conditions. The pressure-velocity coupling was set to the “coupled” scheme and the gradient and pressure were set to “Least Squares Cell Based” and “PRESTO”, respectively. The momentum and energy were set to “Second Order Upwind” discretisation scheme. Radiative heat transfer was modelled using the DO method with a theta and phi divisions and pixilation set to 5×5 . The DO method also used “Second Order Upwind” discretisation. Each simulation was run for 5000 iterations and was considered converged when the energy residuals and DO intensity residuals fell below 10^{-6} , and the momentum residuals fell below 10^{-4} . All simulations successfully converged using the CFD strategy outlined after the specified number of iterations.

3.3.3 Material properties and boundary conditions

The external fluid is set as air, and the internal fill gas is set as nitrogen, which is a typical nonreactive gas used in QTH lamps [43]. The viscosity for air and nitrogen, are determined using the power law provided by *Mazor et al.*, where μ_{ref} for both gases at 300 K were obtained from *Incropera et al.* [17]. The surface properties for the quartz and tungsten are defined using five wavelength bands of between 0.3–1, 1–2, 2–4, 4–6 and 6–8 μm . Using blackbody waveband tables [16], this wavelength range was found to account for >99% of wavelengths emitted at 3000 K and >98% at 2500 K and thus is deemed to be suitable wavelength range for comparison to the experimental data.

The absorption coefficient of the quartz for each of these wavebands is determined based on the absorption index data provided by *Kitamura et al.* [146] and piecewise polynomial equations which fit this data provided by Mecit [123]. The absorption coefficient was calculated for 100 evenly spaced wavelengths across each waveband, and the average of these values was used as the absorption coefficient value in the model. The refractive index was determined using a similar method, again using the data from *Kitamura et al.* [146]. Forsythe and Adams [147] provided the spectrally averaged emissivity of tungsten from 0.3 – 4 μm over a range of temperature which was used in this work. The emissivity for a given wavelength band was determined using the 2D interpolation for a given temperature. As recommended by Forsythe and Adams, the tungsten emissivity for wavelength greater than 4 μm can be calculated using Drude’s formula, which shows good agreement with the experimental data. The emissivity of the quartz is not a direct user input in the model but instead inferred from

the absorption coefficient [25]. Further details of the material properties used in this work can be found in Appendix C.1.

The power input boundary conditions were matched to the experimental measurements by defining a heat generation rate within the bulk of the tungsten material. For each of the power input levels investigated, the heat generation rate was determined by dividing the experimental power input by the volume of the filament specified in the numerical model. The pressure inlet and outlet were set to have an emissivity of unity, and a radiation temperature of 300 K. The emissivity of aluminium varies with both wavelength and temperature [148] and therefore to simplify the analysis it was assumed to be a constant value of 0.2 across all wavelength bands. Since the surfaces of the aluminium base and tungsten filament cannot be considered optically smooth (i.e. RMS surface roughness is $< \lambda / (32 \times \cos \theta)$ [23]), radiation incident on these surfaces will be reflected through a combination of both specular and diffuse regimes. The fraction of specular to diffuse radiation is a function of the roughness of the surface and wavelength of the radiation, which is challenging to account for accurately. Therefore, the total reflectivity of both the aluminium base and the tungsten filament is assumed 50% diffuse and 50% specular since for an unpolished surface both regimes would be expected to contribute significantly to the overall reflectivity. This assumption was validated not to have a meaningful impact on either the temperature of the filament or the overall radiative efficiency of the lamp with fully specular or fully diffuse surfaces resulting in $< 0.2\%$ change in each when compared to the 50% specular and 50% diffuse case. Furthermore, the quartz is assumed to be optically smooth and to transmit radiation 100% specularly similar to other modelling research involving this material [145].

3.4 Results and discussion

3.4.1 Experimental radiative efficiency

Fig. 3.4 presents the radiative efficiency of the QTH lamp as the power input is increased from 426 W to 925 W along with the experimentally measured filament temperature. Both the radiative efficiency and the temperature of the filament monotonically increase with the input power across the voltage range tested. The maximum efficiency measured was 94.7% at 230 V with a corresponding radiative power output of 876 W, and the minimum efficiency was 90.9% at 140 V at a corresponding radiative power output of 387 W. This represents approximately 5.3% and 9.1% in convective losses for the 230 V and 140 V test points, respectively. The filament temperature rises from a minimum value of 2470 K to a maximum value of 2960 K across the same range. The primary driver for the observed trend of increasing efficiency with voltage and power input is the discrepancy in the nonlinear dependence of the convective and radiative heat transfer with increasing source-ambient temperature difference. This was illustrated for the case of an electrical heater by *Brown et al.* [140] where the radiative and convective heat transfer coefficients (HTC) were shown to diverge as the temperature of the heated surface is increased: the radiative HTC monotonically increased with surface temperature while the convective HTC plateaus at quite low surface temperatures after an initial increase. Therefore, as the power input to the lamp is increased, the proportion of heat transported by radiation increases disproportionately compared to heat transported by convection.

Besides the relationship between the radiative and convective HTCs, there are other factors which directly influence the efficiency of the lamp: (a) the conductivity of the fill gas which increases with temperature and hence convective losses are exacerbated at elevated temperatures; (b) the spectrally averaged emissivity of tungsten which increases with temperature; therefore, heat will be transported more preferentially by radiation at higher filament temperatures; (c) the spectral absorptivity of the quartz envelope which increases at longer wavelengths; hence, more radiation will be absorbed at lower filament temperatures where a longer wavelength distribution will be emitted from the surface of the source. Although the impact of each of these individual factors is difficult to quantify, overall, it is clear that they combine to result in an improvement in radiative efficiency as the filament temperature is increased.

Comparing this data to the literature, the research of Pettersson & Stenström's [36] model

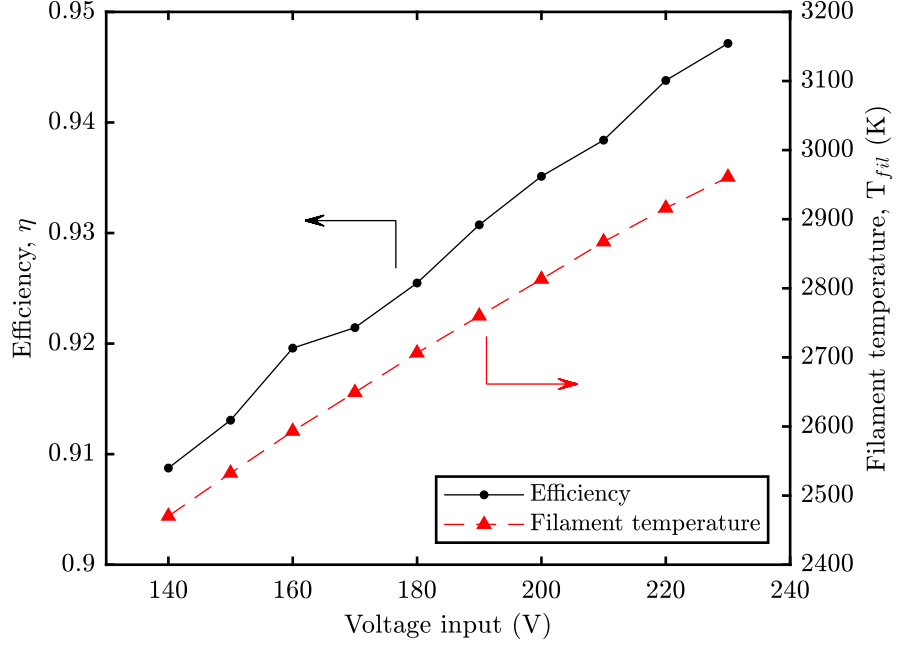


Figure 3.4: Experimentally measured radiative efficiency and filament temperature vs input voltage for the QTH lamp.

predicted a maximum of 83% efficiency for their QTH lamp and Bedard [35] measured between 76%-86% efficiency for two types of QTH lamps measured at the lamp's maximum voltage of 420 V. These efficiencies are lower than those measured in this work, however, this may be explained by a number of factors. Both research groups carried out testing on double-ended connector lamps which may have different thermal performance when compared to single-ended counterparts. Furthermore, as noted by the authors in the modelling work carried out by Pettersson & Stenström, the Neon fill gas has a higher thermal conductivity when compared to other fill gases and, therefore, will likely result in lower radiative efficiencies. Also, the maximum temperature of the filament tested by Pettersson & Stenström was ~ 2200 K, which is considerably lower than the lowest temperature of the QTH lamp in this work. Finally, Bedard measured the efficiency using an in-plane technique of lamps which were part of a reflector system which will be subject to errors not encountered using the spherical heat flux mapping technique (i.e. accounting for the absorption of the radiation on the metallic reflectors).

3.4.2 Spherical heat flux mapping

Fig. 3.5a and b show the experimentally measured spherical heat flux map of the QTH lamp at a voltage input of 140 V and 230 V. Most notably, these figures indicate that the heat flux output from the top of the lamp is comparatively much lower than other areas as illustrated clearly in Fig. 3.5c for the 230 V test. Additionally, there are “wave” patterns evident on the maps when traversing longitudinally from pole to pole. The lower heat flux areas and the wave patterns are a function of the varying view factor between the heat flux sensor and the filament source as the lamp is rotated longitudinally from 0 to 360°. When the sensor is at an angle of 180° relative to the axis of the lamp (i.e. inline with the long axis), the view of a large proportion of the coiled surface is blocked by neighbouring filament coils which therefore results in lower heat flux levels when compared to when the sensor is located at longitudinal angles closer to 90° or 270° (i.e. perpendicular to the long axis). Similarly, as the lamp is rotated, a portion of the filament surface will be visible at a given angle, and at other angles, this portion of the surface will be shaded by neighbouring sections of the coiled structure. This gives rise to the varying heat flux patterns. As shown in Fig. 3.5d, there is also an area of reduced heat flux at the south pole of the spherical map where the shadow of the base of the lamp and the aluminium holding jig block radiation from reaching the sensor. As a result, the hermetic seal around the molybdenum connectors and lamp base will be heated to a high temperature. Molybdenum will begin to oxidise at ~620 K [28], which if exceeded, will eventually cause the failure of the lamp, although the exact temperature limit of the seal may depend on factors such as the geometry of the quartz envelope and if an anti-oxide coating has been applied to the molybdenum.

This spherical heat flux mapping and radiative efficiency measurement technique was initially described by *Brown et al.* [140] using a 6-axis robot arm, however, this research shows that it can be performed without the need for a complex positioning system by merely rotating the radiation source with a relatively low-cost chuck and spindle. This has the additional benefit of allowing the use of a windowless heat flux sensor as the device never enters the rising plume of heated air. Overall, the potential to accurately measure the heat flux output and determine the radiative efficiency of a compact radiating source such as QTH lamp has been demonstrated using this technique.

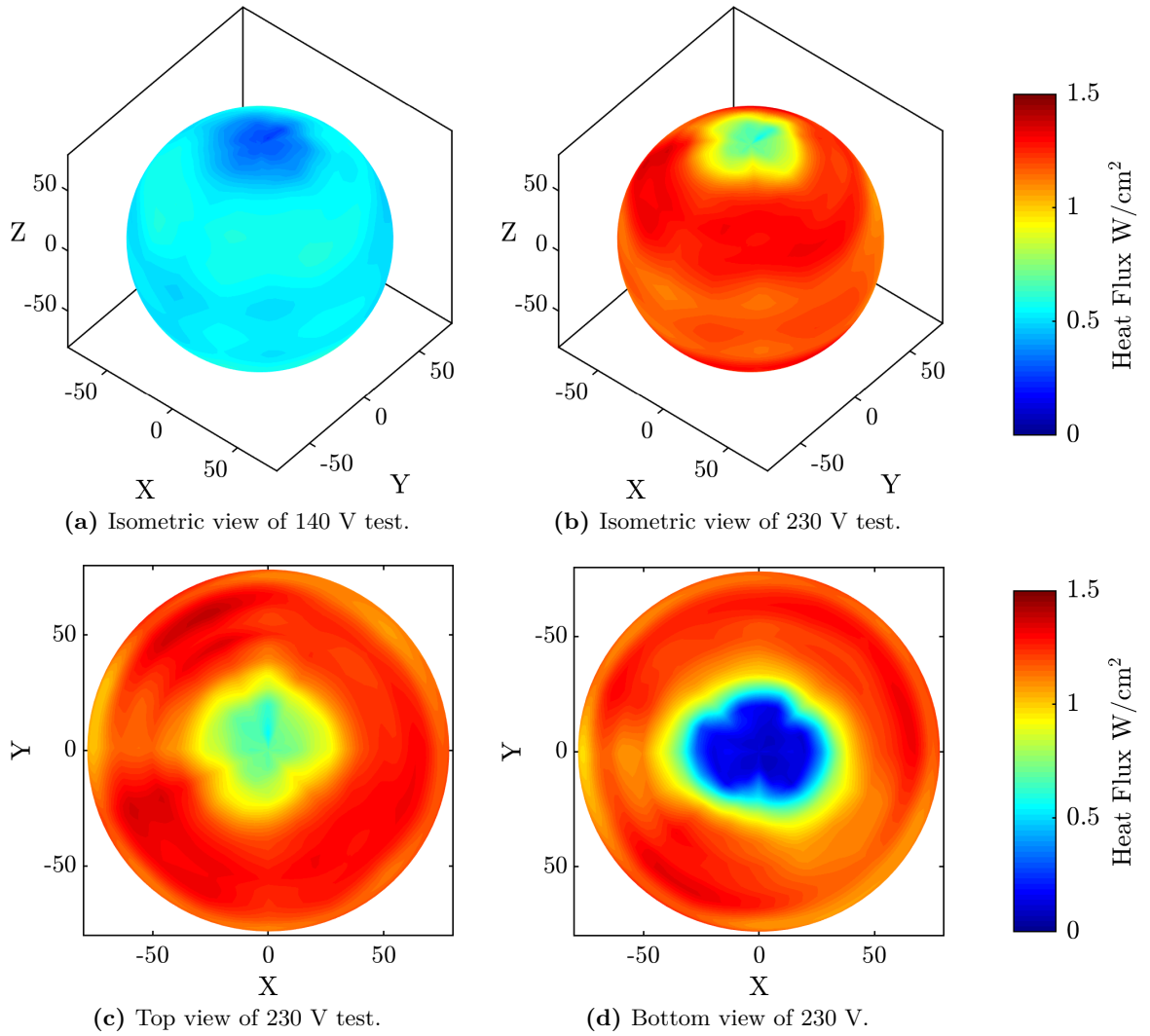


Figure 3.5: Spherical heat flux maps of the QTH lamp at 140 V and 230 V with 78.3 mm radius from the filaments geometric centre.

3.4.3 Comparison to the numerical model

Fig. 3.6 presents the experimental radiative efficiency measurement versus the numerical simulation prediction. The numerical simulation reveals a similar trend to that which was experimentally measured with the predicted radiative efficiency of 88.4% delivered at 140 V and 92.3% at 230 V. This data aligns well with the experimental measurements, with the simulated radiative efficiency falling just below the uncertainty bars across the entire range of voltages tested. The experimentally measured filament temperature and numerically simulated filament temperature are also plotted against the input voltage in Fig. 3.6. The simulation predicts a lower filament temperature than was experimentally measured across the test range but within the uncertainty of $\sim 4.3\%$. The difference between simula-

tion predictions and experimental measurements may be accounted for by the experimental uncertainties discussed in section 3.2.4; however, there are other factors directly related to the model construction which may also explain the differences: (a) a discrepancy between the surface area of the filament of the actual QTH lamp and of the simulated lamp will strongly affect the temperature of the filament; (b) in reality, the tungsten filament is not the only surface which transfers heat as the molybdenum supports also participate through radiative and convective heat transfer; (c) finally, the simulated configuration of the filament is different from that of the QTH lamp in order to allow axisymmetric modelling. Although all of these factors, among others, may affect the accuracy of the model, it is still deemed to predict the experimental results sufficiently well to allow further investigation into the physics underlying the performance of the lamp.

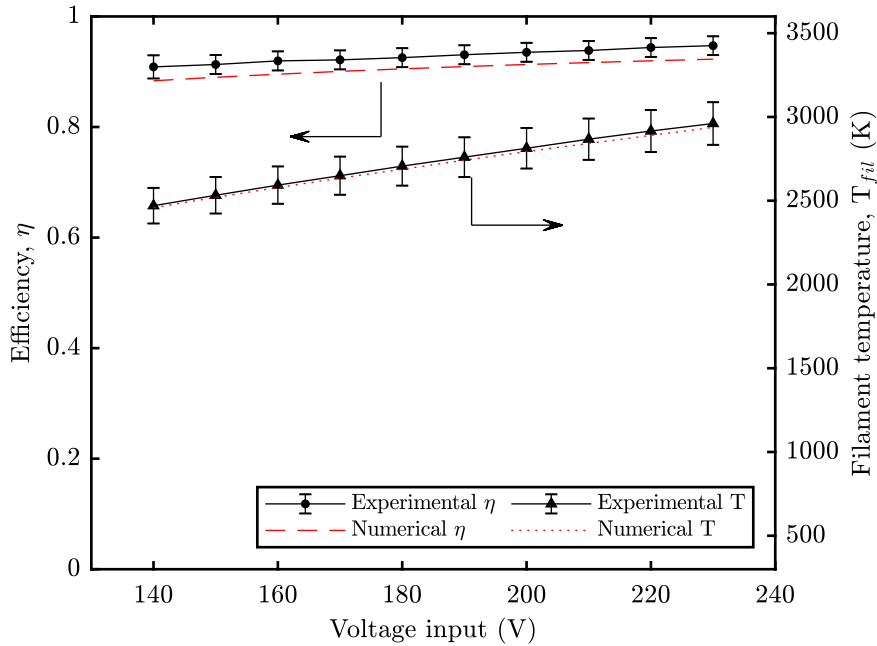


Figure 3.6: Comparison between the experimental measurements and numerical model with 95% confidence interval error bars and the numerical model prediction for radiative efficiency and filament temperature.

3.4.4 Analysis of the numerical model

In this section, the numerical model is used to explain the mechanism for the high thermal efficiency of greater than 90% for this particular lamp. The heat flow through the system can be partitioned as illustrated in Fig. 3.7 for the 230 V test case. As depicted, a significant fraction of the heat is emitted from the filament by radiation and exits directly to the ambient

environment (91.1%), whereas a smaller portion is absorbed by the quartz envelope (4.0%) and lamp and holder system (0.5%). The low absorption of radiation by the quartz envelope, base, and holder is due to the high transmissivity of the quartz, and high reflectivity of the aluminium surfaces. Convection transports 4.5% of the power from the filament to the quartz envelope. Of the 78.5 W transported into the quartz envelope through the combined effects of convection and radiation absorption, most of this is transported to the ambient air by convection. The remainder of the heat (8.3 W) leaves the quartz envelope by conduction into the base and holder. The base and holder emit all of the heat absorbed into the body through radiation due to the high surface temperature of ~ 820 K. This temperature is actually cooler than the outside flow which results in convection transporting a small amount of heat into the base and holder (0.7 W). For the case where gravity is inverted and the heated air flow does not pass over the holder, the temperature of the holder is considerably lower at ~ 640 K which therefore results in heating being transported more preferentially by convection to the surroundings from these bodies. The minimum base temperature predicted by the model was ~ 520 K for the lowest power tested experimentally where the heated flow did not pass over the base and holder. The difference in base temperature is the primary factor results in the marginally higher efficiency ($\sim 1\%$) of the lamp while inverted due to the rising plume of heated air passing over the base and holder.

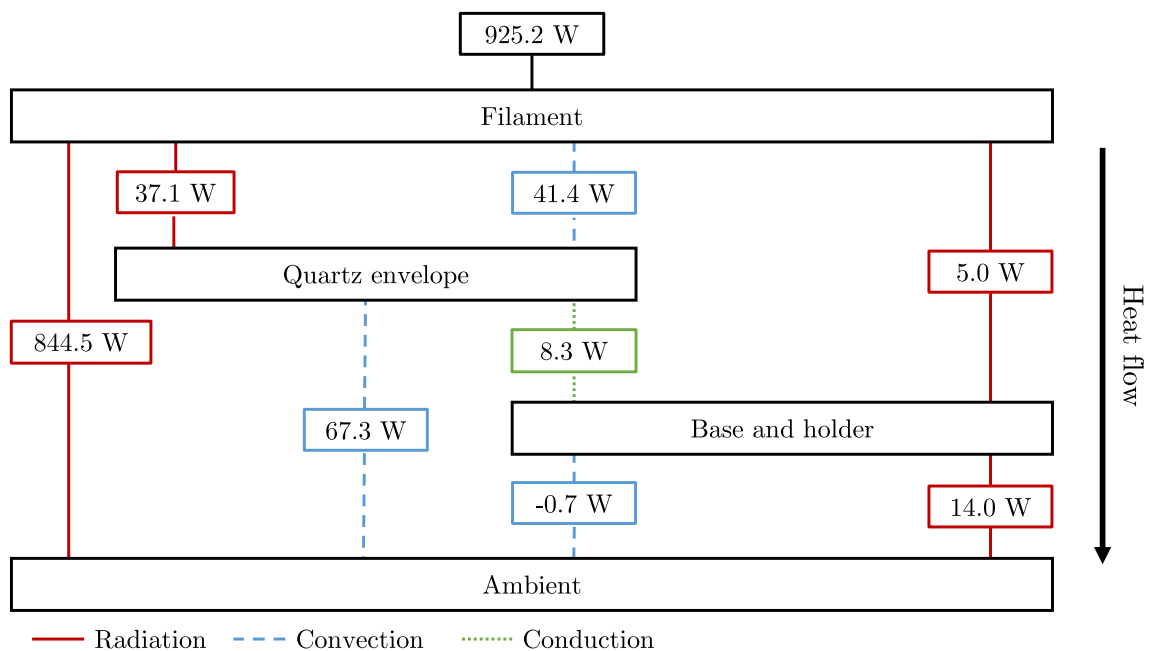


Figure 3.7: Heat flow partitioning of the lamp from the filament to the ambient heat sink based on the numerical model results for the 230 V test.

From Fig. 3.7, it is clear that the losses are accounted for almost entirely by the convective heat transfer from the outer surface of the quartz envelope; the base and holder system is close to neutral in terms of convective losses and in fact, contribute to the radiative heat transfer of the overall system. Of the heat transfer to the quartz envelope, convection from the filament makes up the majority (53%). Therefore, the properties of the fill gas are likely to play an important role in the overall efficiency of the system. The primary reason for the high thermal efficiency of the lamp system is due to the vast majority of the power input to the lamp exiting directly from the lamp by radiation emitted from the filament which is virtually unimpeded by the highly transmissive quartz envelope. However, the physical reason for the high rate of radiation heat transfer originating from the filament in comparison to convective heat transfer is not immediately apparent but can be explained in terms of HTC's.

Fig. 3.8 plots the power dissipated from the filament versus the convective HTC at the outer surface of the quartz envelope together with the radiative HTC at the filament surface. A power law fit of each of these data sets are also provided with R^2 values of >0.995 . The radiative HTC from the filament and the convective HTC from the quartz envelope represent the main transfer mechanisms from the source to the surroundings and thus can be used to understand the high rate of radiation heat transfer from the lamp. The radiative HTC is defined as:

$$h_{rad} = \varepsilon\sigma(T_{fil} + T_{\infty})(T_{fil}^2 + T_{\infty}^2) \quad (3.24)$$

where ε is the spectrally averaged emissivity of the tungsten filament, and σ is the Stefan-Boltzmann constant. The convective HTC is defined as:

$$h_{conv} = \frac{Q_{quartz, conv}}{S_{quartz} \times \Delta T_{quartz}} \quad (3.25)$$

where, $Q_{quartz, conv}$ is the parasitic heat lost by convection on the outer surface of the quartz, S_{quartz} is the outer surface area of the quartz, and ΔT_{quartz} is the difference between the average outer surface temperature of the quartz and the external air flow. As described in section 3.4.1, there is a nonlinear dependence on the temperature difference for both heat transfer coefficients which is highlighted in Fig. 3.8. The convective HTC is predicted to only marginally increases from 9 to 16 W/m²K across the simulated power input range of 10 to 925 W. A power law regression of the convective HTC shows that the HTC is not strongly influenced by the power input, with an exponent of only 0.12. The increase in the

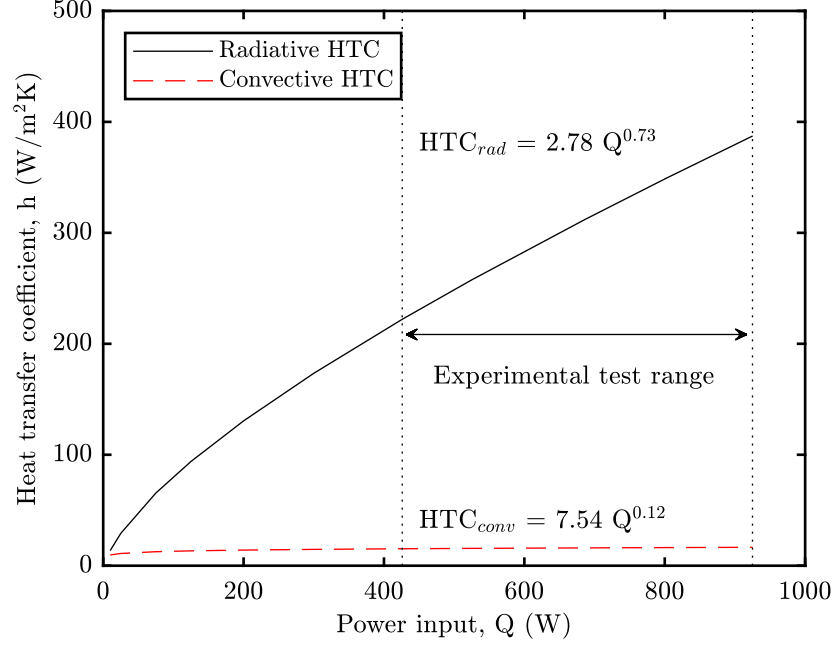


Figure 3.8: Radiative and convective HTC of the QTH lamp determined using the numerical model.

convective HTC is attributed to the change in the thermophysical properties of the fluids with temperature, most notably the thermal conductivity which increases with temperature for air and other ideal-like gases [17].

Conversely, the radiative HTC somewhat monotonically increases as the power input to the filament is increased. Initially, the radiative HTC was comparable to the convective HTC at the lowest power input of 10 W, rising from 14 W/m²K to over 380 W/m²K at the maximum power of 925 W. In this case, the radiative HTC coefficient is more strongly influenced by the power input to the lamp with an exponent of 0.73 for the power law fit. As the power to the filament is increased, the surface temperature increases and heat is removed more preferentially from the surface by radiation. For the experimental test range, the radiative HTC varies from 14 to 23 times greater than the convective HTC – this ratio is what gives rise to the thermal efficiencies of between 90-95%.

It is clear that the radiative HTC is the dominant factor which defines the radiative efficiency, and based on Eq. 3.24, h_{rad} is dependent on the temperature of the filament. Thus, filament temperature and radiative efficiency of the lamp are strongly correlated, as was previously shown in the experimental data presented in Fig. 3.4. Higher efficiencies could be obtained at higher source temperatures, however, the rate of evaporation of the tungsten drastically rises at temperatures above 3000 K which degrades the operating life of the lamp

through hot spot formation [41].

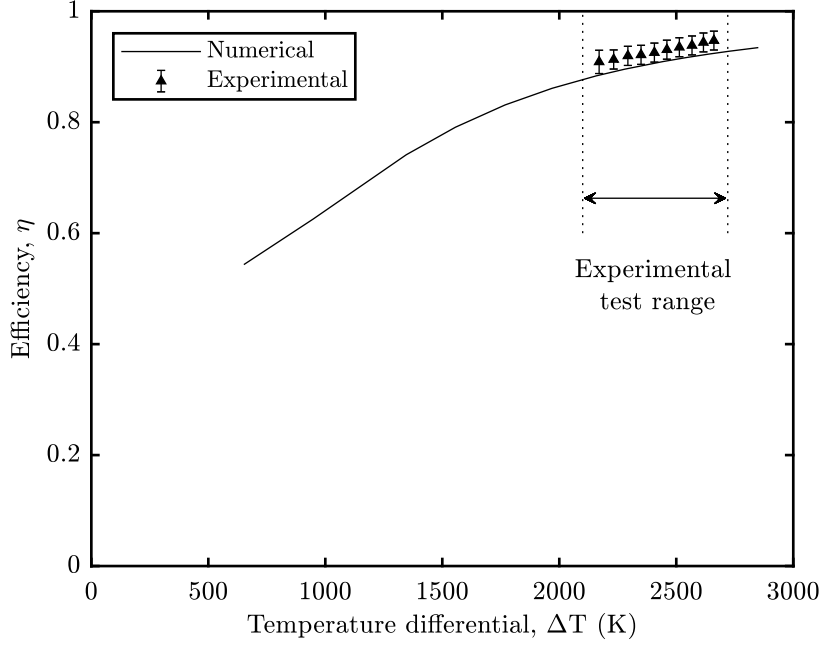


Figure 3.9: Temperature-efficiency curve for the QTH lamp based on the numerically simulated filament-ambient temperature differential vs radiative efficiency from 700 K to 2800 K. The experimentally gathered data for an ambient temperature of 300 K is also shown.

The numerical model can also be used to predict radiative efficiencies outside of the measurement range possible with the current experimental setup. Fig. 3.9 shows how the simulated efficiency varies with temperature with the efficiency as low as 54% at $\Delta T = 700$ K and over 93% at $\Delta T = 2800$ K. The experimental data gathered in this research is also included for comparison. The overall trend is asymptotic meaning that an increase in temperature differential does not affect the efficiency proportionally across the entire range. For example, at $\Delta T = 1000$ K, a 10% increase in temperature differential results in a 5% relative increase in the radiative efficiency while at a $\Delta T = 2000$ K a 10% increase in temperature difference results in a 2% relative increase in efficiency. The temperature efficiency graph in Fig. 3.9 may be used as an estimate for the radiative efficiency for researchers employing this exact lamp or other single-ended lamps of a similar design. The author suggest a high level of caution when applying this efficiency curve generally to QTH lamps; there are many factors that will affect the radiative efficiency and may vary from lamp to lamp such as the overall size and shape, the outer temperature of the quartz envelope, the absorptivity of the quartz and the thermophysical properties of the fill gas. Although this curve may not predict the efficiency of a wide range of lamps to a high degree of accuracy, the prediction will

be significantly improved when compared to assuming 100% electrical-radiative efficiency as was used in previous studies.

3.5 Conclusions

Experimental analysis and numerical model development of a QTH lamp has been performed and detailed. The QTH lamp is experimentally found to radiate at efficiencies of between 90% and 95% and is correlated to the filament temperature and hence to the input power. The modified heat flux mapping technique posed was demonstrated to be a viable approach which can be used to characterise the thermal performance of small radiating bodies such as QTH lamps. The temperature of the filament was experimentally measured to vary between 2470-2960 K for the power inputs tested. The measured radiative efficiency of the lamp was found to be higher than that of the previous research which may be accounted for by the different types of QTH lamps tested and the lower source operating temperatures employed during the testing of these lamps. The spherical heat flux maps show that the lamp emits an uneven distribution of radiation, which is primarily due to the presence of filament supports and the view factor between the sensor surface and the filament. Also, a derivation for the filament coil diameter based on accurately measurable or known quantities was provided and employed in the development of the numerical model domain.

The axisymmetric model has been shown to predict the radiative efficiency of the lamp well with efficiencies of 88-92% and filament temperatures of 2460-2940 K across the experimental power range tested; therefore this modelling approach can be utilised when investigating the performance of a given QTH lamp or other similarly sized radiating bodies with quartz envelopes. An explanation for the higher thermal efficiency was provided based on the differences between the radiative and convective HTC's. Finally, a new efficiency curve has been developed which will allow other researchers to estimate the efficiency of similar QTH lamps through measurement of filament temperature.

Chapter 4

Benchmarking of FIRH limits

4.1 Introduction

This chapter will discuss the characterisation of the SpotIR 4085 commercial FIRH manufactured by Precision Control Systems (PCS). The performance of this device is then compared with the theoretical limits of focused IR technology. This will provide a benchmark for the designs developed later in this work and contextualise the objective of this research from herein.

Throughout this work, the primary metric that will be used to characterise the utility of a FIRH is the heat flux output, since it is proportional to the maximum temperature that can be reached by a target surface under adiabatic conditions. Several commercially available devices specify a “peak” heat flux as the performance metric; however, in this work, heat flux will be specified as an average value over the outlet area of the FIRH. This is a more reliable metric which is a closer representation of the overall performance of the device. Other secondary metrics, such as efficiency and overall length of the FIRHs, will be considered where appropriate comparisons can be made.

The upper limits of the performance of the FIRH will be determined through analysis of the system via the first and second law of thermodynamics. This will allow limits to be defined for the power, heat flux output, and the temperature reached by the target surface. A well-defined upper and lower limit for the FIRH will present a design window from which the performance of the FIRHs developed in this work can be compared. The goal of the work in the following chapters can therefore be understood as reducing the gap between the current FIRH performance and the specified theoretical limits.

4.1.1 SpotIR heater

As discussed in the literature review, the SpotIR heater by PCS is a low-cost FIRH, which is primarily used for curing, soldering, and metal annealing. This device was selected for characterisation as it provides a high peak heat flux over a relatively large area which implies the device can be applied to a wide range of applications. Power output is not specified by the manufacturer, but instead, the heat flux distribution is provided. This data is replotted in Fig. 4.1a for the 14 mm diameter outlet area. The peak heat flux is $\sim 100 \text{ W/cm}^2$, whereas the area-weighted average over the entire outlet is a lower value of $\sim 78 \text{ W/cm}^2$. Multiplying the average heat flux by the outlet area results in a power output of 120 W and efficiency of 16%. This must not be confused with the power output and efficiency calculated by reference [14], which only considered the heat flux over a 6.35 mm focal diameter. The manufacturer did not specify the methods used to measure the heat flux output such as the type of heat flux sensor, if the sensor was calibrated, the dimensions of the sensing element, nor the distance away from the outlet. Therefore, this data must be taken in the context of this absence of information.

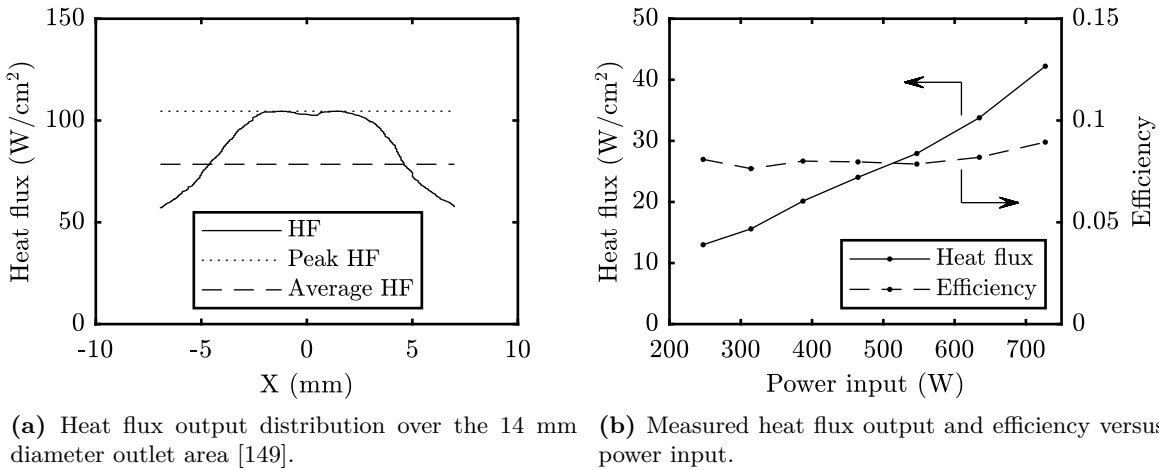


Figure 4.1: Performance of the Precision Control System SpotIR heater.

This device was also characterised in this work using a power output measurement, which can be subsequently converted to an average heat flux by the division of the outlet area. The power output measurement was taken directly at the outlet of the device using a commercial power meter (FLASH-500-55-C, Gentec, Canada) which employs the thermopile measurement technique. This power meter will be used for all of the power output measurements in this work. Discussion of the validation of this device can be found in Appendix C.2.

The heat flux output and efficiency of the device measured in this work are shown in Fig. 4.1b with efficiency defined as the radiative power output measurement divided by the electrical power input. The max power output delivered by this device was 65 W over a 14 mm diameter area which is 42 W/cm². The average efficiency of the device was ~9%, which is approximately half of the value calculated by the heat flux distribution. This discrepancy may be due to several factors. Firstly, the device was extensively used before testing, and therefore could be subject to degradation of any number of parts, but in particular, the reflector may not be as reflective as when originally manufactured due to oxidisation of the Al surface. Secondly, the technique used to measure the heat flux output by the manufacturer is subject to errors not encountered by measuring the power output and inferring the heat flux (i.e. the weighting of the heat flux based on the area of the circular annulus at a given radial distance). A combination of both sources of error is likely to contribute to this discrepancy.

4.1.2 Thermodynamic limits

The thermodynamic limits which constrain the performance of the FIRH are outlined below.

4.1.2.1 The radiative power output of the FIRH

The first law of thermodynamics states that the total energy in a closed system is conserved. This implies that the radiative output of the system will be limited by the radiative power output of the source. For the 1000 W lamp studied in this investigation, the radiative efficiency of the lamp was measured to be ~95% at 3000 K with corresponding radiative power output ~880 W. Therefore, the first limit on the performance of the FIRH is that the radiative power output from this lamp cannot exceed this value.

4.1.2.2 Target temperature

The second law of thermodynamics asserts that entropy must increase during spontaneous or irreversible processes. Hence, heat can only flow from areas of high temperature to areas of low temperature in a passive system. It is therefore apparent that the temperature of the heat sink cannot be higher than that of the heat source which is ~3000 K. Although, in practice, the maximum temperature will be considerably lower than this value due to thermal losses during the transfer of heat from the filament to the target.

4.1.2.3 Étendue

Étendue has been described as the 2nd law of thermodynamics applied to optical systems [91], and this property can be used to define an upper limit for radiation transfer from a source to a target. Using the equations outlined by *Sun et al.* [93], the étendue of the cylindrical filament source can be determined for the 750 W lamp (21 mm length $\times$ 5.8 mm diameter cylinder) used by the SpotIR heater:

$$\dot{E}_{fil} = \pi^2 \times D \times h = 1200 \text{ (mm}^2\text{sr)} \quad (4.1)$$

The étendue of a 14 mm diameter disk target can be calculated:

$$\dot{E}_{disk} = \pi^2 \times r_{max}^2 \times \sin^2\theta_{max} = 615 \text{ (mm}^2\text{sr)} \quad (4.2)$$

Where θ_{max} is the outlet angle, which in this case is assumed the theoretical maximum of 90°. Therefore, the maximum efficiency of the device based on this étendue analysis is the ratio between these values, which is determined to be 51%. The effect of a skewness difference between the source and target may also reduce the maximum permissible radiative transfer. However, as described in section 2.3.5, higher efficiencies than this may be possible due to the effect of light recycling. This will be considered in detail later in this work in section 6.6.5 and section 8.4.2.

4.1.2.4 Heat flux output

As discussed in the opening of the literature review, the second law of thermodynamics sets a limit on the heat flux output of the FIRH. Similar to the fact that heat must flow from areas of high concentration to low concentration in a passive system, the heat flux at the outlet of the FIRH cannot exceed the heat flux output of the tungsten halogen source under normal circumstances.

Using the Stefan Boltzmann equation with a specularly averaged emissivity of 0.33, the maximum heat flux from a tungsten filament at 3000 K is as follows:

$$q''_{max} = \varepsilon \sigma T^4 = 0.33 \times 5.67 \times 10^{-8} \times 3000^4 \approx 150 \text{ (W/cm}^2\text{)} \quad (4.3)$$

However, this calculation assumes that the emitted radiation does not interact with the

filament (i.e. the surface is convex and not surrounded by a highly reflective enclosure). In the case of a coiled tungsten filament, light recycling will play an important role in increasing the effective radiance of the source at the cost of a power output reduction as described by *Fu et al.* [47]. At this point in the investigation, it is unclear to how large a degree light recycling will improve the radiance of the filament employed, although it is assumed to be higher than the value of 30% found in the research of *Fu et al.* due to the double-coil construction of the filament. Furthermore, the reflector of the FIRH will practically enclose the filament, which will increase the likelihood of radiation emitted from the surface re-intercepting the filament. As a result, it is difficult to quantify the theoretical limit without knowledge of the final reflector geometry. Therefore, the blackbody radiation rate can be specified as the upper theoretical limit for the filament:

$$q''_{max, blackbody} = \sigma T^4 = 5.67 \times 10^{-8} \times 3000^4 = 460 \text{ (W/cm}^2\text{)} \quad (4.4)$$

Although the actual limit is likely to be lower than this value and will be highly dependent on the operational temperature of the filament, this number will provide context regarding the maximum permissible heat flux output from an ideal FIRH.

4.2 Comparison to commercial devices

Fig. 4.2 plots the heat flux output of the PCS device and a range of devices provided by Thermo Riko. Also shown is the theoretical maximum heat flux for a blackbody at 3000 K. These devices were selected for comparison as they are reliably characterised, have high power outputs and are suitable for a range of applications outside of soldering. Other FIRHs listed in Table 2.1 on page 38 may have improved performance in terms of heat flux but either specify a peak heat flux (and provided no heat flux distribution or details on the measurement technique) or deliver power outputs so low that they are not useful outside of soldering. Out of the selection of FIRHs discussed in Chapter 2, the Thermo Riko and PCS devices are the most relevant to this work.

As shown in Fig. 4.2, the PCS and Thermo Riko FIRHs fall short of the theoretical maximum of convex tungsten with the highest heat flux from the GL398 unit delivering 75% of the limit. This figure illustrates a design window where the current performance of the FIRHs reside on the lower end, while the theoretical maximum for blackbody resides on

the upper end. Hence, the primary goal of this research (i.e. improving the performance of focused IR technology when compared to commercial devices and the theoretical limit) can be illustrated using Fig. 4.2. As a result, this figure will be updated as this work progresses and improved FIRHs are developed.

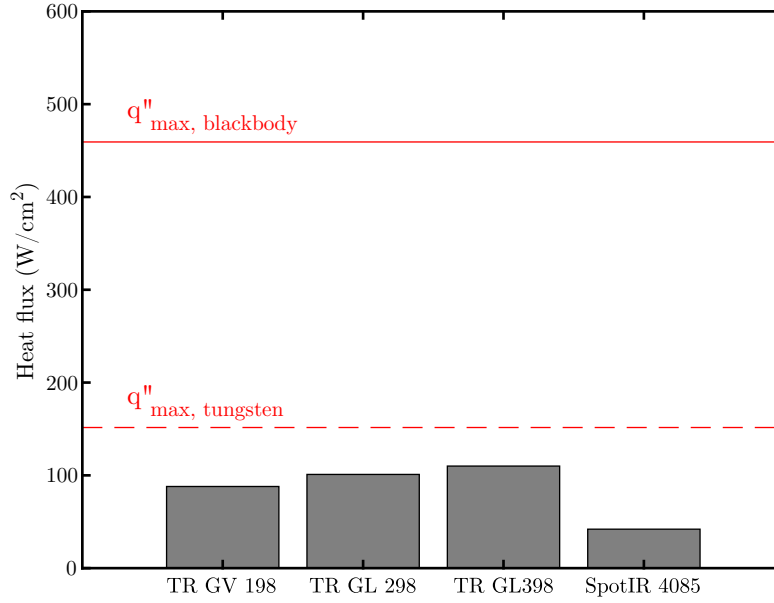


Figure 4.2: Heat flux output of various FIRHs compared to the theoretical maximum. TR and PCS refer to Thermo Riko and Precision Control Systems respectively.

Chapter 5

2D MCRT model development

5.1 Introduction

This chapter describes the methodologies used to design and optimise a FIRH using a 2D MCRT approach. The proposed design methodology is first outlined, which utilises an automated optimisation strategy coupled with MCRT. The remaining sections of the chapter explain the development of the necessary features required to realise the optimisation process, the assumptions applied during modelling, and the physical aspects associated with simulating a radiation-based problem.

5.2 The selected optomechanical design process

As outlined in the summary of the literature review, the chosen optomechanical optimisation process is composed of the following features:

1. Shape parameterisation to define the geometry of the reflector.
2. MCRT to perform the “fitness” evaluation of each shape.
3. A genetic algorithm (GA) to determine which shapes to test for fitness and control the convergence towards a global optimum.

The interaction of these components is illustrated in Fig. 5.1 and explained as follows:

Step 1: The GA creates a random population of candidate shape solutions within the geometric constraints placed on the size and shape of the reflectors. For example, in the case of a FIRH, the minimum dimensions may be constrained by the size of the source while volume or weight specifications may dictate a maximum size. The limits must be carefully selected to ensure that optimal solutions do not fall outside of the limit window; alternatively, if the limits are too broad, computational power will be wasted evaluating unfeasible solutions and the process may not converge on an optimum as readily.

Step 2: For each solution in the population, the shape must be parameterised, which is achieved using a compact Bézier spline representation with 3 control points.

Step 3: The fitness of each of the candidate solutions is determined using MCRT.

Step 4: The next generation of shapes is formed through the creation of offspring by crossover and random mutation of the parent genes using the GA. As with natural selection, the gene combinations with the highest fitness are more likely to progress to the next generation.

Step 5: Steps 2-4 are repeated, maintaining the initial population size until a specified number of generations or the change in the population performance is below a given threshold.

Step 6: After convergence, the highest performing shape and the population history are saved by the GA.

Each of these steps will be described in more detail in the following sections.

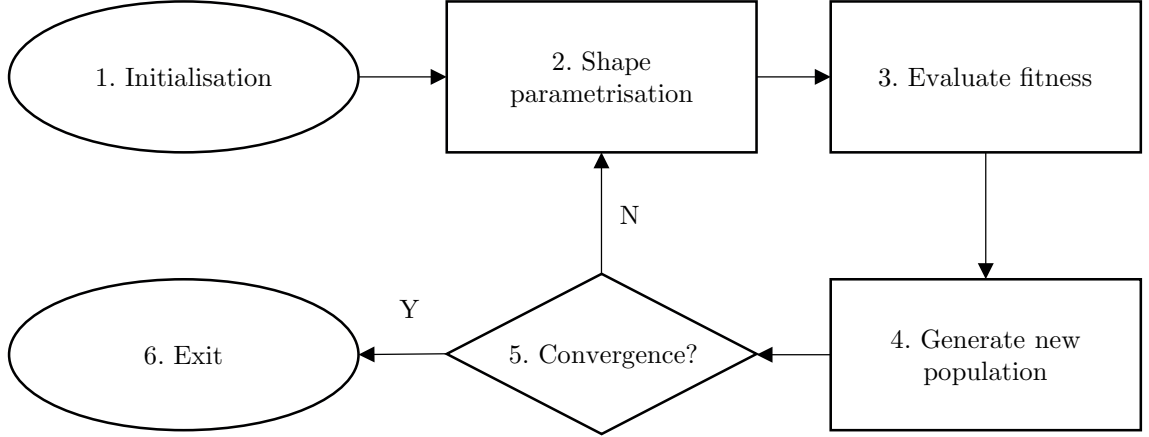


Figure 5.1: Flowchart of the optimisation process.

5.3 Shape parameterisation

A Bézier curve is a type of spline that is often used in shape optimisation problems due to its flexibility and potential to represent a large number of shapes with a small number of control variables. The compact representation makes the Bézier curve method suitable for use with GA as it compresses the design search space into a small number of variables while ensuring the curve is continuous and smooth. A quadratic Bézier curve has three control points, with the endpoints of the Bézier curves located on the first and last control point. The 2nd control point can then be used to manipulate the overall shape of the curve between the two endpoints. An example of quadratic and cubic Bézier curves with control points is illustrated in Fig. 5.2.

A Bézier curve is formed through interpolation of the control point positions and a location-dependent weighting. This can be further explained by analysing the general form of the Bézier curve equation, which is as follows for $0 \leq t \leq 1$ [150]:

$$Q(t) = \sum_{i=0}^n b_i P_i = \sum_{i=0}^n \binom{n}{i} (1-t)^{n-i} t^i P_i \quad (5.1)$$

Here, b_i is the Bernstein polynomial which along with the control points can be expanded for a quadratic case where $n = 2$:

$$Q(t) = (1-t)^2 P_0 + 2t(1-t)P_1 + t^2 P_2 \quad (5.2)$$

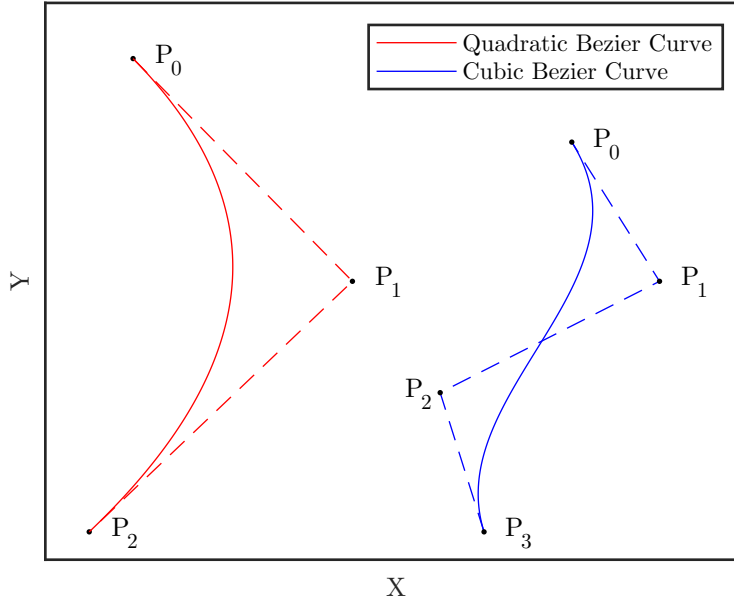


Figure 5.2: Example of a quadratic Bézier curve with three control points and a cubic Bézier curve with four control points.

Moreover, for a cubic case where $n = 3$:

$$Q(t) = (1 - t)^3 P_0 + 3t(1 - t)^2 P_1 + 3t^2(1 - t) P_2 + t^3 P_3 \quad (5.3)$$

Fig. 5.3 illustrates the relative effect of each of the coefficients of the Bézier curve as t is increased. As shown for the quadratic and cubic case, when $t = 0$, all other coefficients tend to zero, and the curve reduces to P_0 . When $t = 1$, the equations reduce to P_2 or P_3 for the quadratic and cubic case respectively. Between zero and one, the Bézier curve falls between these two endpoints, with the exact position dictated by the relative influence and position of the Bézier control points.

A quadratic Bézier curve will be used to parameterise the shape for the 2D prototype model. Although shapes defined using higher-order curves will likely provide improved reflector performance, the optimisation of these shapes requires greater computation time due to the added complexity of the problem, and slower convergence of the GA. Higher-order curves will be investigated later in this work.

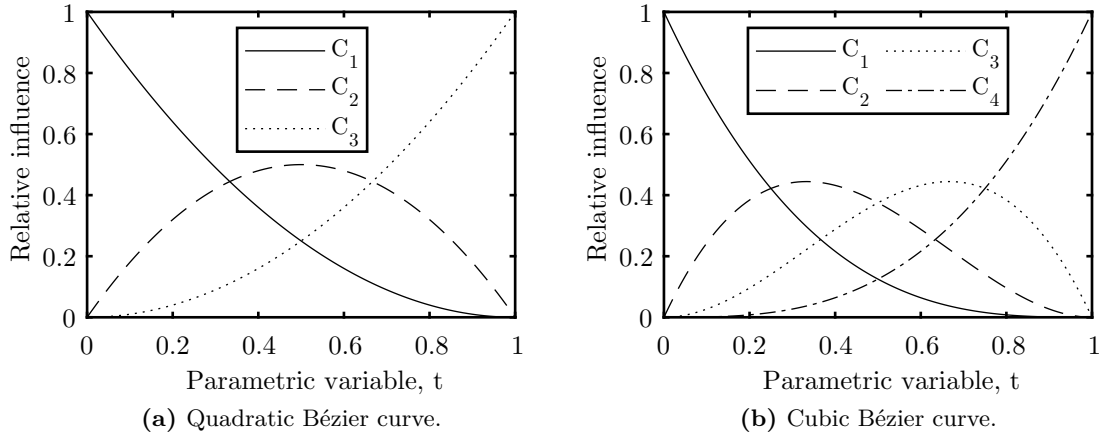


Figure 5.3: The relative influence of each of the Bézier control points as t is increased from zero to one.

5.4 Fitness evaluation

5.4.1 Conjugate heat transfer simulation

A full thermal model of this problem could be employed to characterise the performance of a given reflector shape (similar to that of the model developed in ANSYS Fluent in Chapter 3). This would allow all three heat transfer modes which drive the heat exchange to be modelled and thus the performance of the system to be accurately simulated. However, several issues surround the use of a conjugate heat transfer model implementation:

1. This modelling approach requires taking account of the fluids inside and outside of the quartz envelope, which implies a mesh must be developed for both of these regions. This adds to the computation time and complexity of the model. The robustness of the model may also be questionable since meshing is often a manual process which requires tuning after initial generation. This is problematic for a shape optimisation task where widely varying reflector shapes will be generated, potentially leading to errors and inaccuracy due to invalid mesh elements.
2. The computation time of a conjugate heat transfer model is too long for the requirements of this study. For the case of the model developed in Chapter 3, the solution time was > 1 hour.
3. The model developed in Chapter 3 was axisymmetric, which means nonaxisymmetric features such as the filament supports cannot be taken into account. While this may be sufficient for a measure of the radiative efficiency, ideally a modelling technique

which eventually allows a full 3D representation should be developed for optimising the FIRH. Developing a nonaxisymmetric 3D model in ANSYS Fluent would require much greater computation time than the model developed in Chapter 3 due to the larger mesh size.

Shape optimisation has been performed using a conjugate heat transfer model previously in the work of *Moghimi et al.* [145] where a trapezoidal cavity absorber was optimised with reasonable success. However, relatively few simulations of predefined shapes could be performed due to the complexity and computational requirements of the model. Later work by the same researchers [151] optimised a similar problem set by only considering the radiative heat exchange and neglecting the CFD simulation to reduce computation time. This allowed a more extensive range of shapes to be tested. The convective losses were expected to account for approximately 20% of the total heat transfer, and therefore optimising for only radiative losses was a justified choice.

Given these factors, the limited computational power available, and that the radiative power from the lamp is anticipated to be over 90% of the total electrical power input, neglecting convection is deemed a reasonable assumption.

5.4.2 The Monte Carlo method

As discussed in section 2.5, the MC method is a technique which negates the need to integrate complex formulations which are difficult to solve using traditional numerical methods without applying limiting assumptions. The main advantages of the MC method are as follows:

1. This method is general and can therefore be applied to a wide range of problems, including radiative heat transfer.
2. The implementation of the MC method is simple and robust in comparison to alternative methods that first transform and then numerically solve the radiation transfer equation.
3. An increase in the complexity of the problem does not lead to a proportional increase in computational time.

The main disadvantage of using the MC method is the statistical uncertainty of the solution due to the use of random numbers [89]. The rate at which the MC method converges is proportional to the $N^{-1/2}$, where N is the number of samples employed. Although, this is

independent of the number of dimensions (i.e. complexity of the problem) or the smoothness of the integrand [89].

A MC analysis method was briefly introduced in the literature review with a generalised example of finding π based on the number of randomly seeded points that fell within the bounds of a circle. Given that this work is focused on the development of a RT model, an example of how the MC method can be applied to a RT problem is now demonstrated. This involves the trivial problem of the simulation of the interaction between a photon and an opaque surface such as a polished metallic reflector, as depicted in Fig. 5.4. For the intersection of a ray and an opaque surface, there are two potential outcomes:

1. The ray is reflected by the surface of the reflector.
2. The ray is absorbed by the surface.

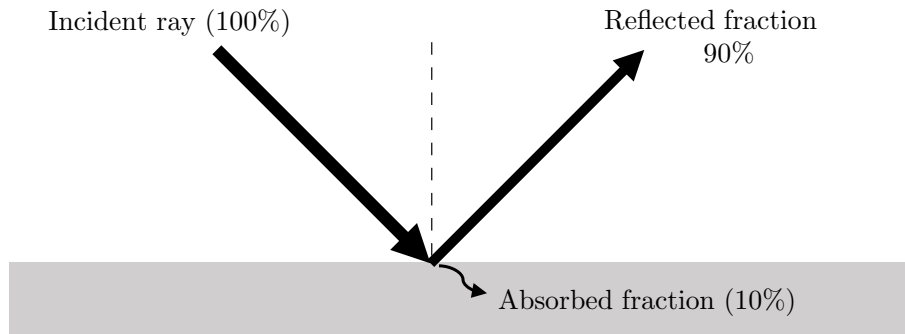


Figure 5.4: Ray intersection with an opaque surface.

The probability of each condition occurring is a function of the reflectance of the material in question. Taking the example of a well-polished Al reflector, depending on the wavelength of the radiation, one could estimate the probability of reflection to be 90%. Thus the ray will be reflected with a probability of 90% or absorbed with a probability of 10%. A random number is generated $R \in [0, 1]$ which selects the outcome in an unbiased manner by comparing the random number to the probability of reflection; if the random number is less than the probability of reflection, the ray is considered reflected, whereas if the random number is greater than the reflectivity, the ray is considered absorbed.

The interaction of a ray with a semitransparent interface is shown in Fig. 5.5. The process is similar for this situation with two outcomes of the ray being either reflected or transmitted. The probability of each is a function of the bulk material properties at either side of the interface and the angle of incidence. The outcome can again be selected using random number generation.

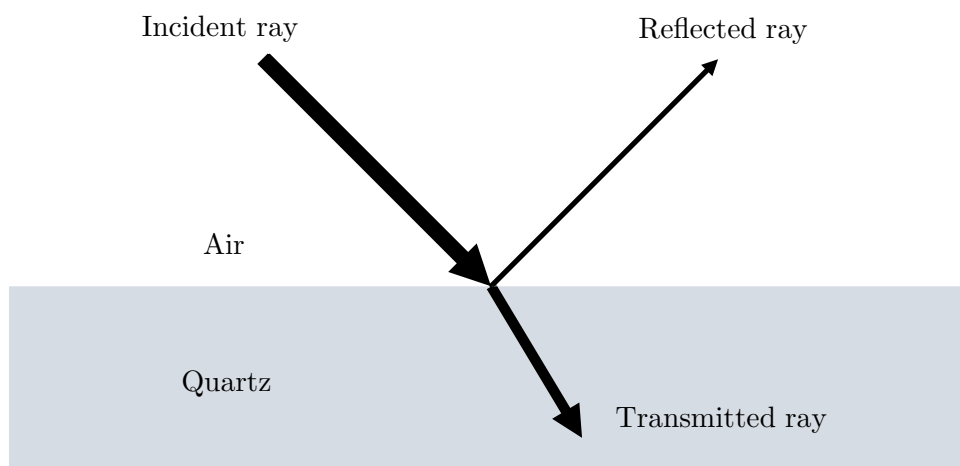


Figure 5.5: A ray interacting with a semitransparent interface illustrating the concept of ray splitting.

There is an important difference between the interaction with a semitransparent material and interaction with an opaque surface. Each outcome of the interaction with a semitransparent material must be traced to a conclusion, whereas for an opaque surface, an absorbed ray is assumed lost and therefore does not need to be traced further. This gives rise to the concept of “split” rays, which greatly increases the complexity of the implementation by the substantial overhead in the management of the ever-growing database of rays with ever-depreciating energy levels. The MC method circumvents this by allowing one outcome to be followed to its conclusion based on the probability of this condition occurring.

The resulting MC framework for RT is one which is much simpler and easier to contend with both from a stability and convergence perspective, but also in terms of model development and ease of incorporation with a range of different problem sets.

The above examples of reflection and refraction are just one aspect of the contribution of the MC method to the modelling of radiative heat transfer exchange within a FIRH. The MC method will also be used to seed rays on the surface of the filament source, determine the direction of emission, assign wavelength distributions, as well as determine the outcome absorption within semitransparent materials. These aspects will be outlined in the following sections.

5.5 2D model development

The shape parametrisation, MC, and RT methods have been outlined, and so the development of the RT code implementation and integration with the MC method can be detailed. Before this, it is necessary to outline the assumptions applied during the development of the model.

5.5.1 Assumptions

The assumptions made during the development of this model are as follows:

- The problem is assumed 2D and that an optimised shape for the 2D case will be optimal for the 3D case. This is a common assumption applied in nonimaging optics design [94].
- Radiation intersecting the lamp inlet orifice is considered lost and is not traced further.
- The fill gas and external gas are assumed not to interact with the radiation and are nonparticipating [45].
- All surfaces besides the quartz envelope are assumed opaque and can only reflect or absorb radiation.
- The filament supports are not possible to include in a 2D model and are therefore disregarded.
- The quartz envelope is assumed to only transmit and absorb radiation and not to scatter.
- No polarisation or birefringence effects are included.
- Diffuse scattering is assumed to follow a Lambertian distribution.
- The contribution of secondary radiation from the quartz envelope is assumed negligible.

Several of these assumptions are required to avoid unnecessary complexity (e.g. neglecting polarisation), while others greatly simplify the modelling process (e.g. 2D assumption) and allow a prototype model to be developed in a more time-efficient manner.

The final assumption regarding the quartz envelope is worthy of further discussion. The temperature of the quartz envelope is likely to be over 1000 K at the highest lamp powers

tested and therefore will provide a contribution of radiation to the overall heat transfer from the lamp to the ambient. However, to accurately determine this contribution, a thermal model would need to be developed which includes the effects of convection on the inner and outer surface of the quartz envelope. This was not feasible using the MCRT model within the timeframe of this work and therefore was neglected.

Although these simplifications may reduce the accuracy of the model, they allow the methodology proposed to be tested and validated before developing a fully functional 3D model.

5.5.2 Model domain

The model domain will be constructed using three elements:

1. A top surface of the reflector in which an opening allows the lamp to be inserted into the enclosure.
2. The exit of the reflector or “target surface” located at the bottom of the reflector.
3. Two mirror-image Bézier curves which define the overall reflector shape.

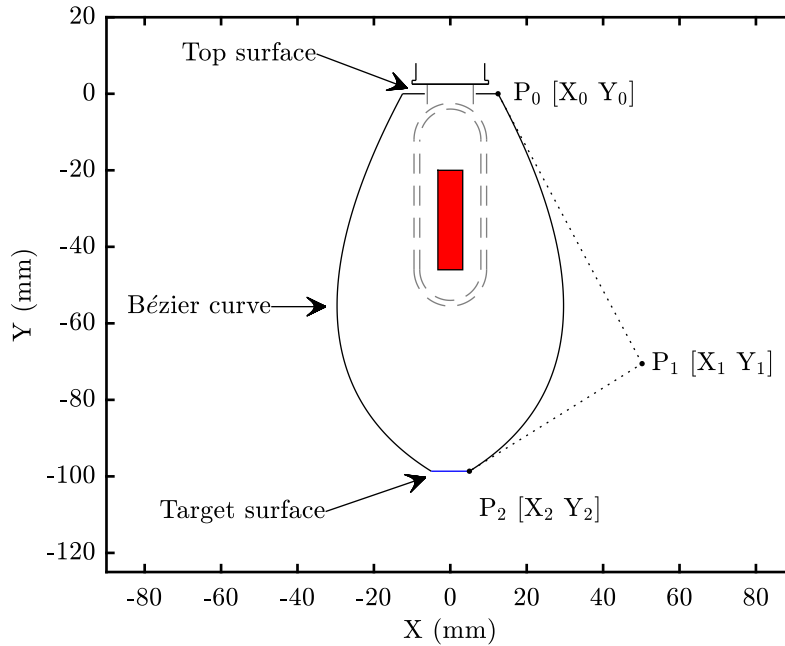


Figure 5.6: Optimisation modelling domain with the Bézier curve shown in black, the filament in red, and the quartz envelope in grey.

The main components of the domain are illustrated in Fig. 5.6. Parts of the domain

must be fixed based on the physical size of the lamp and other related constraints. The first fixed element is the size of the outlet, which must be chosen before the optimisation begins. Secondly, the dimensions of the inlet orifice on the top surface will be fixed based on the dimensions of the lamp. Furthermore, the length of the top surface should be fixed such that the Bézier curve can be used to define the largest proportion of the reflector while still allowing clearance between the reflector walls and the quartz envelope.

The main stages of the MCRT method can be summarised in the following five steps:

1. **Initialisation:** This entails the generation of rays and specifying of the material properties.
2. **Intersection test inside the lamp:** Tests are performed with nearby bodies such as the quartz envelope and filament.
3. **Intersection test within the quartz bulk:** A test for intersection is performed between the interfaces of the quartz envelope.
4. **Intersection test outside the lamp:** If the ray reaches outside of the quartz envelope, a test is performed to determine if the ray intersects with the top surface, target surface, or Bézier curve.
5. **Determine efficiency:** The efficiency of the reflector design is calculated by the number of rays intercepting the target surface as compared with the total rays emitted from the filament.

5.5.3 Initialisation

The flowchart in Fig. 5.7 depicts how each component of the MCRT model interacts. Several of the subroutines have been abstracted away for clarity and will be expanded upon later in this chapter.

During the initialisation step, the model parameters such as the filament temperature and dimensions, number of rays, surface properties, and wavelength distribution of the rays are set. Then for each ray, the following must be set:

- The ray origin
- The initial ray direction vector

- The wavelength of the ray

The equation of the ray can then be defined using vector notation as:

$$R(t_R) = P + t_R \vec{v} \quad (5.4)$$

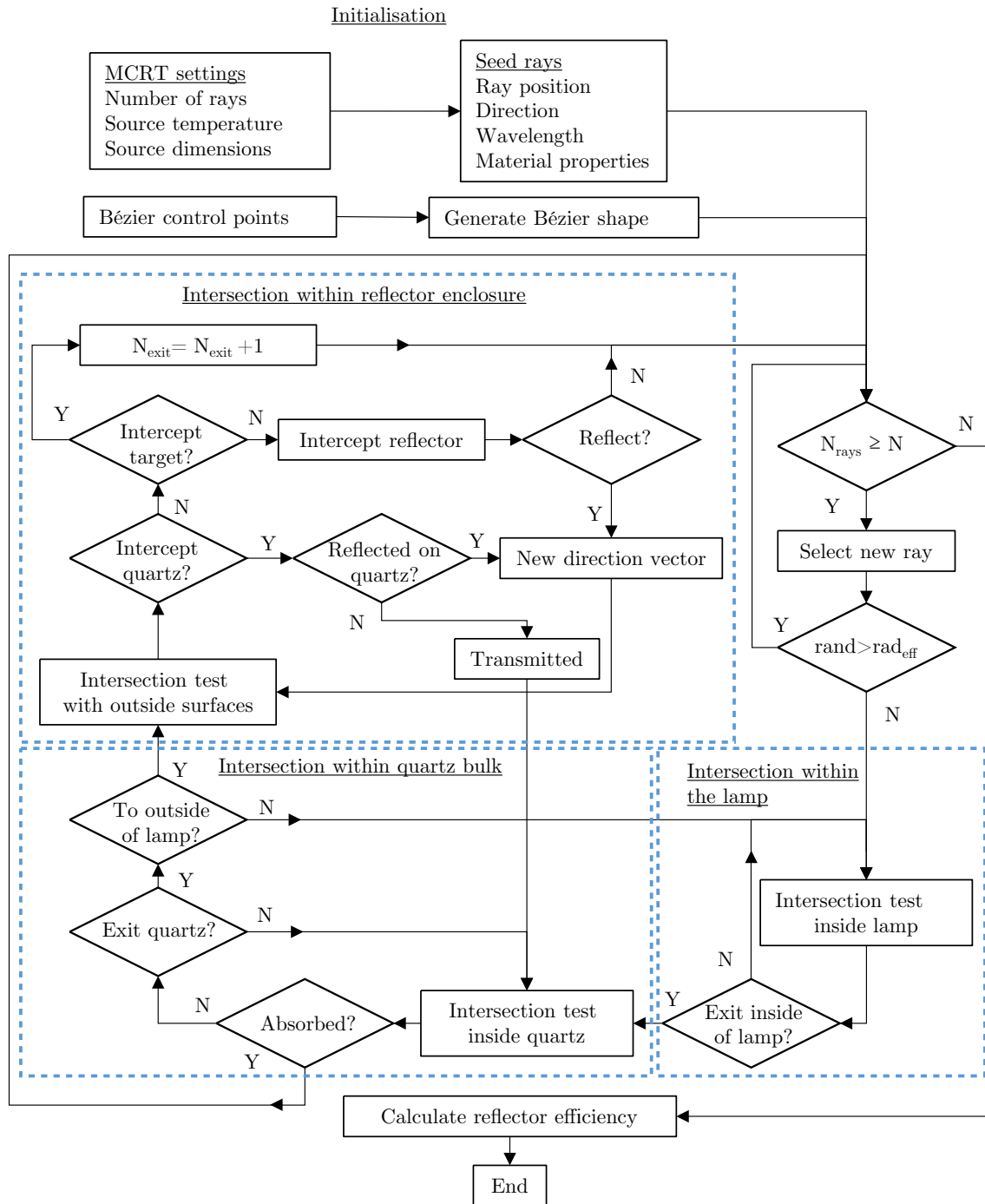


Figure 5.7: Flowchart of the MCRT algorithm.

Where P is a point which the ray passes through, $\vec{v}$ is the vector direction, and t_R is the parametric variable which describes a position along the path of the ray. Next, the material properties associated with each of the rays' wavelength are assigned:

- The reflectivity of the wall
- The index of refraction of the quartz
- The absorptivity of the quartz

This model does not employ wavebands like other numerical modelling techniques, and instead uses a continuous distribution of wavelengths. This approach comes at no additional computation cost when compared to employing wavelength bands, or a single wavelength. For other techniques, the computation time scales linearly with the number of wavelength bands as each band must be integrated independently.

Several ray tracing settings must also be included in the model:

1. The number of rays defines the resolution or accuracy of the ray tracing process with a larger number resulting in a lower statistical uncertainty.
2. The filament is set to a rectangular shape with dimensions of 26 mm height $\times$ 7 mm diameter as provided in Chapter 3, which is representative of a cylindrical emitter in 3D.
3. The shape of the reflector is defined using a Bézier curve with three control points.

5.5.3.1 Seeding of ray origins and vector directions

As discussed in the literature review, there are several strategies to seed the rays on the filament. Firstly, a completely random distribution can be created by first assigning either a random position along the length of the vertical surface or a random width along the horizontal surfaces. This will produce a distribution similar to that of Fig. 5.8a.

Alternatively, a stratified sampling technique can be employed where the points are seeded randomly between uniformly defined boundaries. As discussed, this reduces variance by ensuring that there is a more even distribution of points across the emitting surface. An example of this strategy is shown in Fig. 5.8b.

Finally, a deterministic QMC approach can be employed where the points are evenly seeded along the length of the source. This reduces variance by ensuring that full coverage

of the source is achieved for the given number of seed points. An example of this technique is presented in Fig. 5.8c. Removing as many random processes from the MC model will decrease statistical error, and since the deterministic QMC seeding method is straightforward to implement for this case, it will be used in the 2D model.

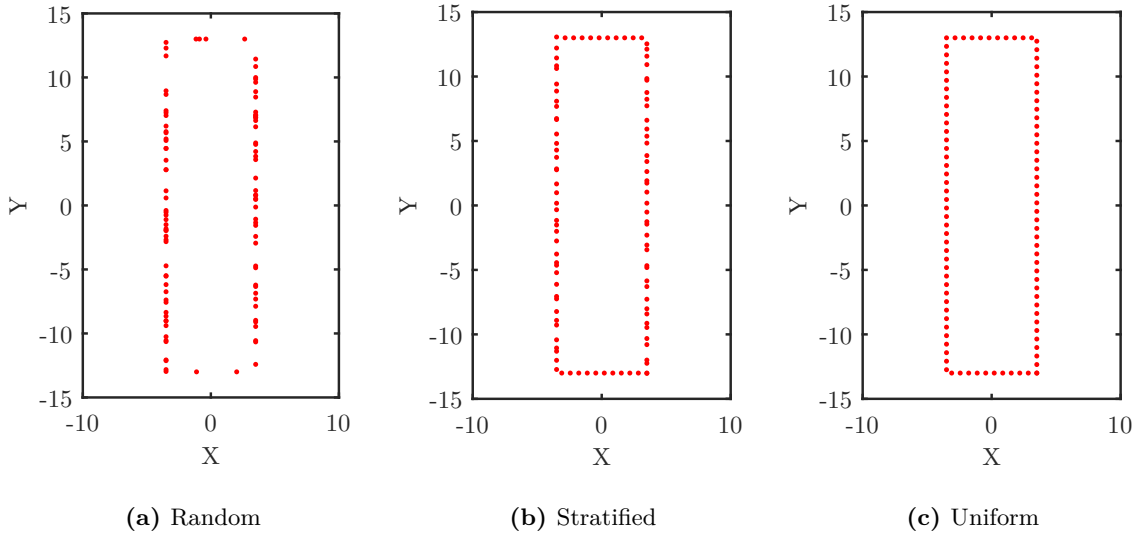


Figure 5.8: Seeding distributions of 100 starting positions for a 2D cylinder source.

Lambertian vector directions The Lambertian distribution for a 3D case is quite common and can be found in many references across the literature [22, 51]. The 2D case is not well documented but can be inferred from the 3D case where the random number $R_1 \in [0, 1]$ is substituted into the following vector formulation:

$$\vec{v} = [\sqrt{1 - R_1} \ \sqrt{R_1}] \quad (5.5)$$

A comparison to a cosine function is shown in Fig. 5.9 demonstrating good agreement.

Once each ray has a random direction assigned, the direction vector is then rotated to the correct position based on the normal vector of the seed location. This can be achieved using a rotation matrix:

$$R_{matrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \quad (5.6)$$

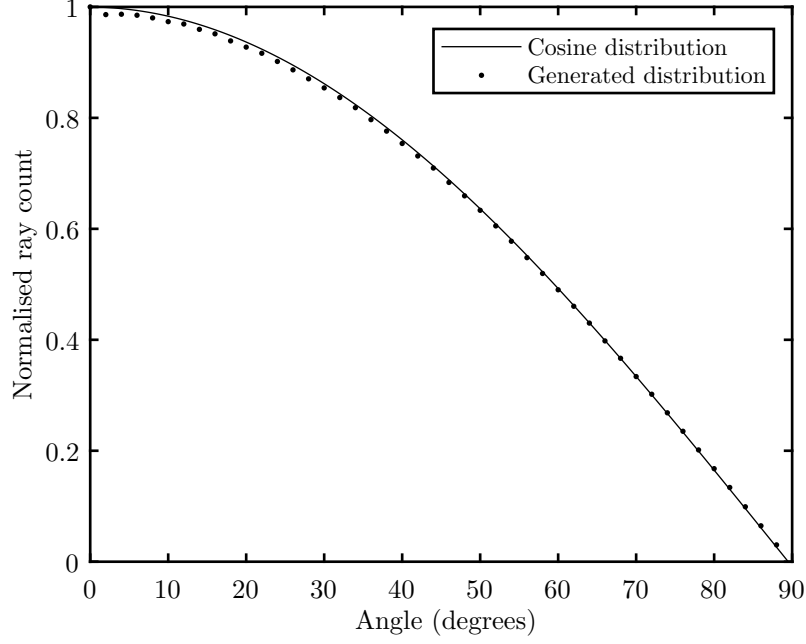


Figure 5.9: 2D Lambertian distribution code validation with 10^8 rays.

Where θ is the angle of rotation from the current position to the final position in the 2D plane.

5.5.3.2 Wavelength distribution

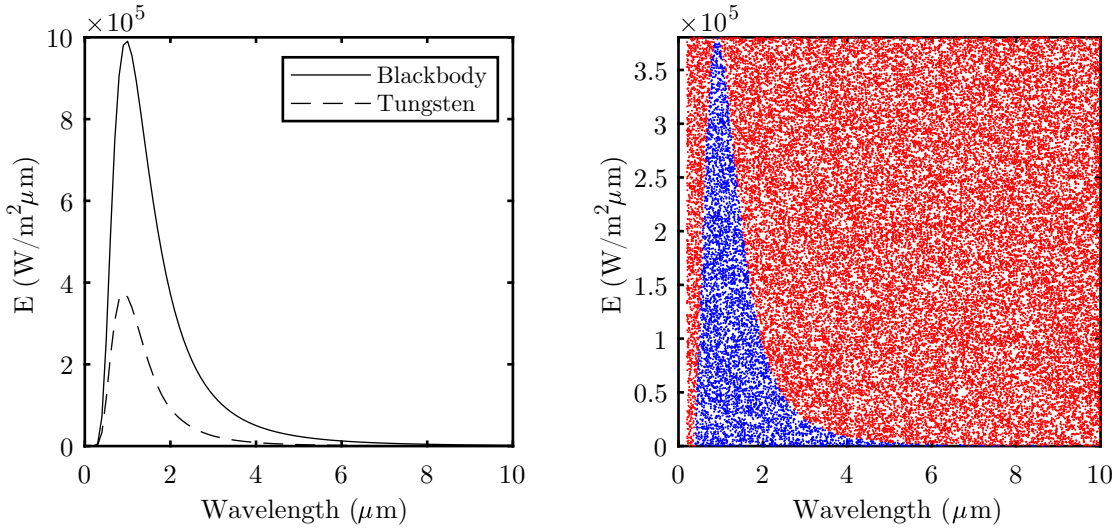
Radiation emanating from a heated body is emitted across a wide range of wavelengths which can be accurately represented by a Planck distribution. Matching the wavelength distribution to that of the Planck function can be achieved by using the “hit and miss” or “rejection” method developed by von Neumann [152]. This involves using random numbers to reject some rays which do not fit within the desired distribution.

For a tungsten halogen source at 3000 K, over 99% of the emitted radiation falls between 0.3-10 μm , and therefore rays are only generated within this range. The spectral power emitted at each wavelength can be determined based on the product of the spectral power of a blackbody and the emissivity of tungsten at a given wavelength:

$$E_{\lambda}(\lambda, T) = \frac{2\pi hc_0^2}{\lambda^5} \frac{1}{e^{\frac{hc_0}{\lambda k_b T}} - 1} \times \varepsilon_{tung, \lambda} \quad (5.7)$$

The rejection function determines a random wavelength $R_{\lambda} \in [0.3 \text{ } 10]$ within the specified range and a random spectral power $R_E \in [0 \text{ } E_{\lambda, \text{max}}]$ where $E_{\lambda, \text{max}}$ is the peak spectral power

for tungsten at a given temperature. If R_E is less than $E_{\lambda, max}$ at the randomly generated wavelength, the wavelength is accepted. Otherwise, the wavelength is rejected, and the process is repeated until the specified number of rays have been assigned a wavelength. An example of the spectral distribution for 5000 rays is shown in Fig. 5.10.



(a) Blackbody and tungsten wavelength distribution at 3000 K. (b) Generated wavelength distribution for tungsten at 3000 K with the accepted ray wavelengths shown in blue, and the rejected wavelengths in red.

Figure 5.10: Wavelength distribution generation between 0.3 and 10 μm using the hit and miss method with 5000 rays.

5.5.3.3 Surface and bulk material properties

The surface properties of the various materials are determined through interpolation of data gathered in this research or via data sourced from the literature. Specular and diffuse reflectivity measurements were obtained using a spectrometer (Perkin Elmer Lambda 900, USA) between the visible and near-IR wavelength range of 0.3 to 1.8 μm in steps of $10^{-3} \mu\text{m}$ for the Al material and Au coating using similar methods to the author's previous work [77]. The reflectivity samples were prepared using the same finishing procedure as the reflector manufactured later in this work, which is detailed in section 6.5.1. The measurement range of 0.3 μm to 1.8 μm data covers $\sim 80\%$ of the spectral emission from a tungsten surface at 3000 K. Since, the reflectivity of Al and Au behave predictably in the IR range, it can be modelled using a combination of the reflectivity data obtained in this work and Drude's formula [147]:

$$\rho = 1 - 0.365 \times \sqrt{\frac{r}{\lambda}} \quad (5.8)$$

The resistivity, r , of an Al-Mg alloy (Al 6082) and pure Au were sourced from reference [153]. Between the wavelength range of 0.3 to 1.8 μm the experimental data is used, over 4 μm Drude's formula is used (which is the cutoff suggested by Forsythe and Adams [147]), and between these wavelengths an interpolation can be carried out. Ideally, a reflectivity measurement across the wavelength spectrum of interest would be obtained; however, no facility to do so was available at the time. Given that the radiometric properties of the metals are predictable across this range, and that only a small proportion of the radiation emitted from the filament is above 1.8 μm , this assumption is deemed to be justified. The total reflectivities of the two samples are plotted in Fig. 5.11 with an overlay of a normalised tungsten emission at 3000 K for context. The diffuse and specular fractions for the Al and Au samples are shown presented in Appendix C.1 as well as comparison to the data from the literature, demonstrating good agreement.

The bulk properties for quartz and the emissivity of tungsten were obtained from the same source as described in Chapter 3. However, instead of discrete wavebands, the data is interpolated to determine the value at each of the wavelengths seeded by the MC simulation. It is noted that this data is for generic quartz and not the specific quartz tested in this work.

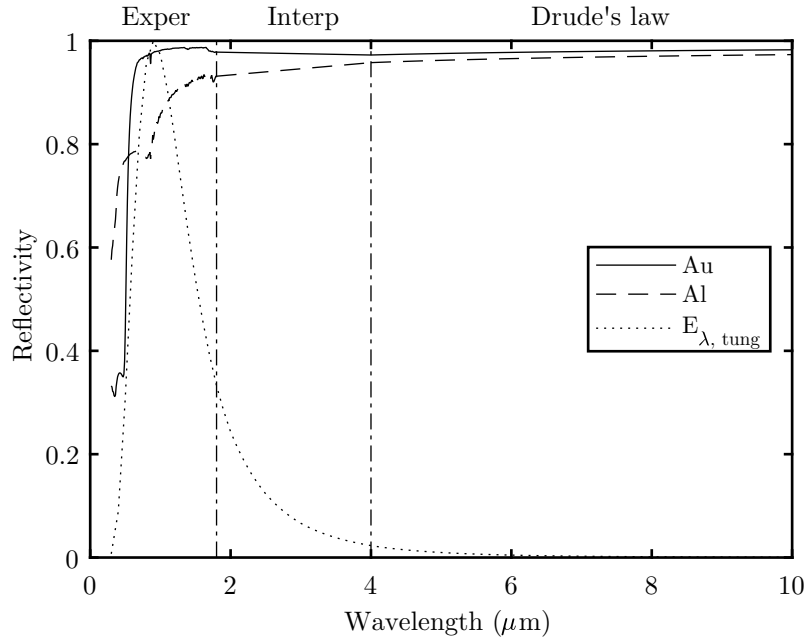


Figure 5.11: The reflectivity of Al and Au wall materials with a normalised tungsten spectral emission distribution at 3000 K.

5.5.4 Tracing inside the lamp

This subroutine is initiated upon first seeding the rays or when the ray re-enters the inside of the lamp, as shown in the overall MCRT flowchart illustrated in Fig. 5.7. The detailed flowchart of this section of the model is presented in Fig. 5.12. The intersection of the ray is tested with the quartz envelope and the filament, which are defined using primitive shapes. Intersection with both of these bodies is tested at each iteration, and the correct solution is determined based on the premise that the solution is real (i.e. not a complex number), the solution is in the same direction as travel of the ray, and the intersection does not occur at

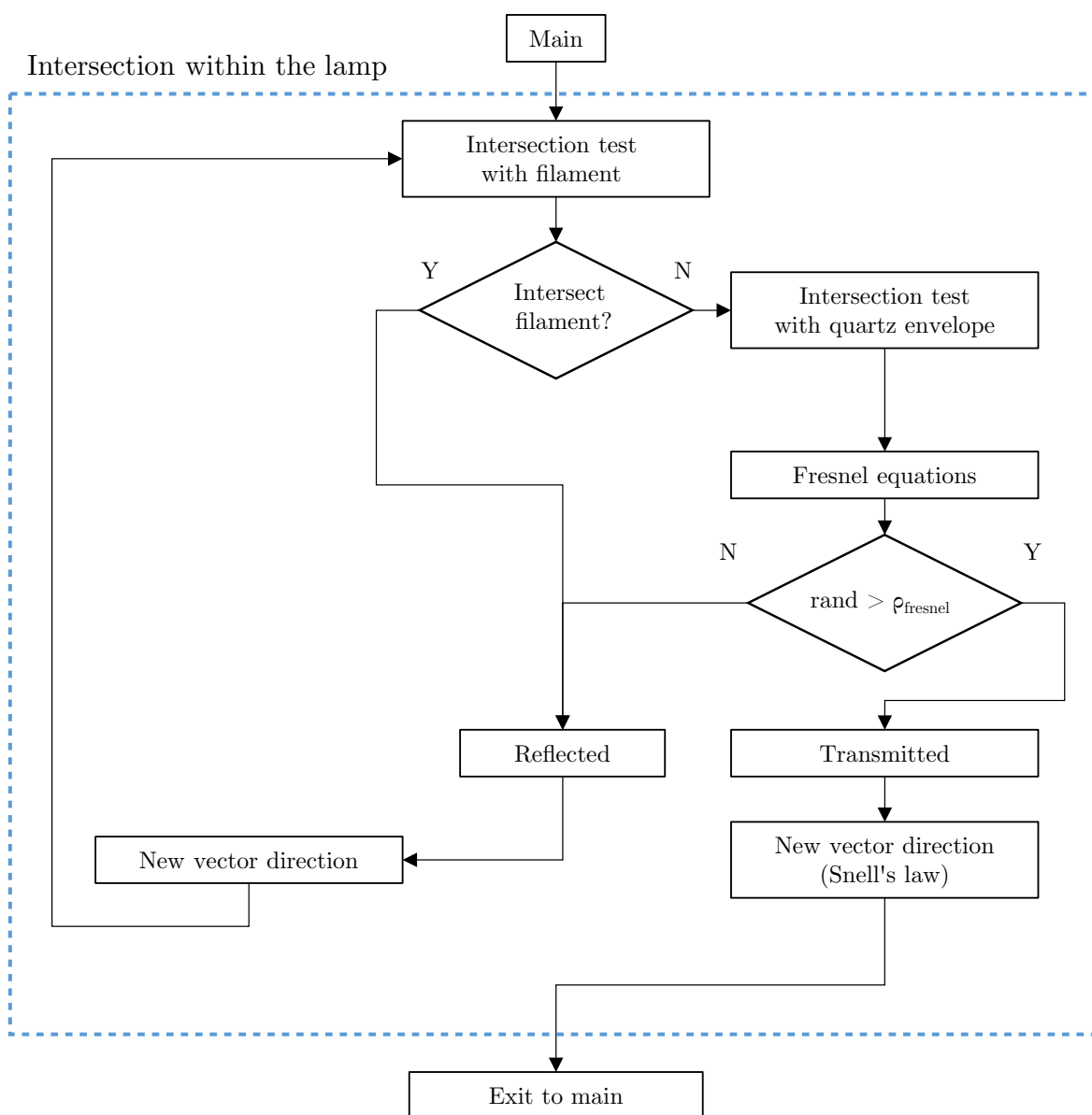


Figure 5.12: Flowchart of the subroutine for a ray propagating inside of the quartz envelope.

the same location as the previous (within tolerance of 10^{-6} mm). This process will leave at least one intersection point within the quartz envelope since the ray is enclosed. If there is more than one valid intersection point, the closest intersection along the ray path is chosen. When the final intersection point has been selected, the state of the ray must be determined (reflected, absorbed, or transmitted). This is based on whether the ray intercepts the quartz envelope or the filament.

5.5.4.1 Quartz envelope

The quartz envelope is defined using two lines and two semicircles for each interface between the quartz and external air or internal fill gas. Two vertical lines also define the base of the quartz. Intersection with the lamp can be tested by performing individual intersection tests with the lines and semicircles that compose the shape of the quartz envelope. The base of the lamp is defined as two lines with a diameter that provides an equivalent cross-sectional area as the square profile of the quartz base. Various intersections and their solutions are shown in Fig. 5.13a.

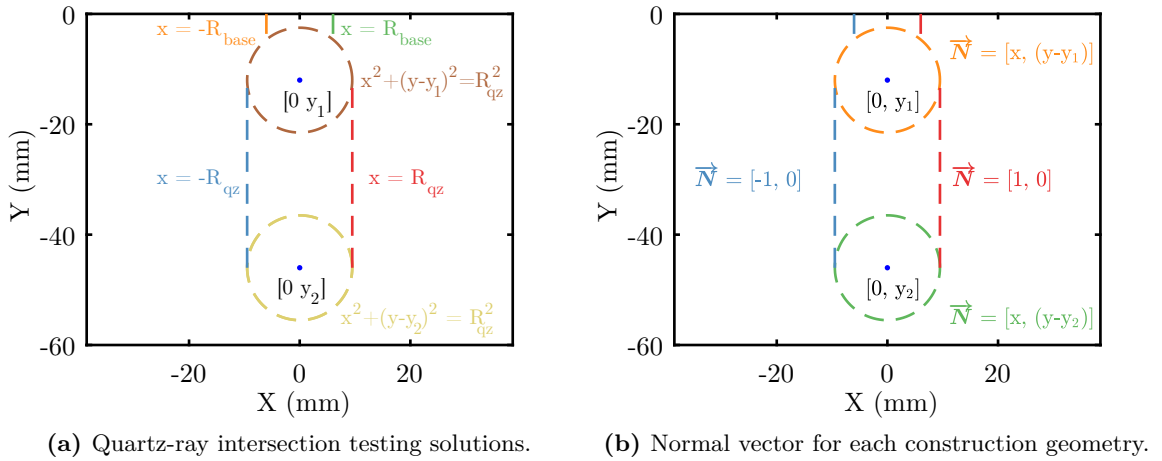


Figure 5.13: Construction of the quartz interfaces.

If the ray intersects the gas-quartz interface, the probability of reflection and transmission must be determined. The physics of this interaction is predicted accurately by Fresnel equations which return the perpendicular ($\rho_{\perp}$) and parallel ($\rho_{\parallel}$) polarisation reflectivity for a given angle of incidence, refractive index, and absorptive index. For an introduction to modelling radiation through interfaces and use of the Fresnel equations, chapter 18 of reference [24] by Siegel and Howell is suggested. The form of the Fresnel equations that

include the effect of absorption was implemented using a method similar to Turner and Ash [51]:

$$\rho_{\perp} = \frac{a^2 + b^2 - 2 a \cos\theta_i + \cos^2\theta_i}{a^2 + b^2 + 2 a \cos\theta_i + \cos^2\theta_i} \quad (5.9)$$

$$\rho_{\parallel} = \rho_{\perp} \frac{a^2 + b^2 - 2 a \sin\theta_i \tan\theta_i + \sin^2\theta_i \tan^2\theta_i}{a^2 + b^2 + 2 a \sin\theta_i \tan\theta_i + \sin^2\theta_i \tan^2\theta_i} \quad (5.10)$$

$$a^2 = \left([(n^2 - \kappa^2 - \sin^2\theta_i)^2 + 4n^2\kappa^2]^{1/2} + (n^2 - \kappa^2 - \sin^2\theta_i) \right) / 2 \quad (5.11)$$

$$b^2 = \left([(n^2 - \kappa^2 - \sin^2\theta_i)^2 + 4n^2\kappa^2]^{1/2} - (n^2 - \kappa^2 - \sin^2\theta_i) \right) / 2 \quad (5.12)$$

Here, θ_i is the angle of incidence, and n and κ are the refractive index and the absorptive index, respectively, which for the gas-quartz interface is as follows:

$$n = n_q; \quad \kappa = \kappa_q \quad (5.13)$$

For the quartz-gas interface:

$$n = \frac{n_q}{n_q + \kappa_q}; \quad \kappa = \frac{\kappa_q}{n_q + \kappa_q} \quad (5.14)$$

In this formulation, the refractive index of the gas is assumed to be one, and the absorptive index zero ($n_g = 1$, $\kappa_g = 0$). The average reflectance is then calculated by assuming that the effect of polarisation is negligible and thus, the two components can be averaged:

$$\rho_{ave} = \frac{\rho_{\perp} + \rho_{\parallel}}{2} \quad (5.15)$$

The transmission angle of the ray can be determined using a modified version of Snell's law, which accounts for the effect of absorption in conjunction with the refractive index:

$$\sin^2\theta_t = \frac{\sin^2\theta_i}{n^2 + \kappa^2} \quad (5.16)$$

The new vector direction can then be found [154]:

$$\vec{v}_t = \frac{n_1}{n_2} \vec{v}_i - \vec{N} \left(\frac{n_1}{n_2} \cos(\theta_i) - \sqrt{1 - \sin^2(\theta_t)} \right) \quad (5.17)$$

If the ray is reflected, either by the transparent media or any other body, Snell's law of

reflection can be used, which in vector form is:

$$\vec{v}_r = \vec{v}_i - 2\vec{N}(\vec{v}_i \cdot \vec{N}) \quad (5.18)$$

where $\vec{v}_i$, $\vec{v}_t$, and $\vec{v}_r$ are the incident, transmitted and reflected vector directions respectively and $\vec{n}$ is the unit normal vector.

The normal vector at the intersection surface is determined based on which part of the quartz the intersection occurs on as illustrated in Fig. 5.13b. It must be ensured that the normal vector is not pointing in the same direction as the ray vector, which is checked by validating that the angle between the two vectors is greater than 90° . If the angle between the vectors is less than 90° , the normal vector must be multiplied by -1. Also, the normal vector must be normalised to a unit length vector before it can be used in Eq. 5.17 or 5.18.

5.5.4.2 Tracing the filament source

Intersection with the filament and the ray is challenging to handle given that the filament is both an emitting and absorbing medium. A full thermal model such as the one developed by Logerais [43] or the ANSYS Fluent model utilised in Chapter 3 would allow the convective and radiative heat transfer from the filament surface to be modelled in its entirety. However, for a model where the calculation of convection is ignored, a method must be developed to ensure that convection losses are accounted for correctly.

Many models developed in the literature assumed that the filament is transparent and does not interact with the radiation once the ray has been emitted [137–139]. This dramatically simplifies the problem and is a justified assumption when contending with an open reflector where the radiation emitted from the surface is unlikely to interact with filament again. For an enclosed reflector shape, there will be many internal reflections and interactions with the emitting surface, and therefore, the filament cannot be considered transparent for this problem.

An alternative approach is to assume that the filament is an emitter-reflector similar to the work of Tuner and Ash [51]. This is a more appropriate assumption which allows the effect of a filament “shadow” to be perceived. However, this research failed to take into account the radiative efficiency of the lamp and thus assumed that all electrical power input is converted into radiation.

The approach taken in this work is similar to that of Turner and Ash, in that the fila-

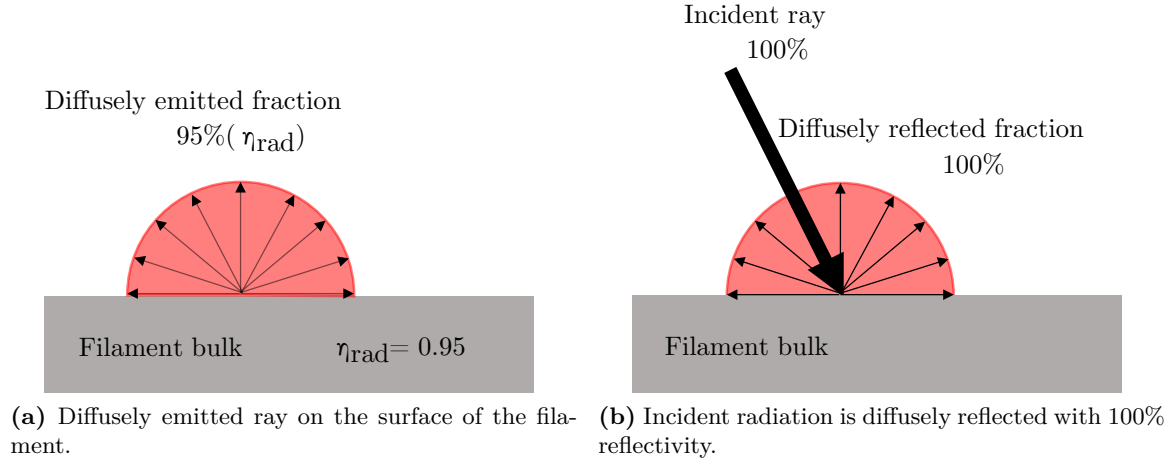


Figure 5.14: Illustration of the procedure for filament intercepts.

ment is assumed to be an emitter-reflector. However, during the initial emission of radiation, the radiative efficiency is used to determine the fraction of rays (i.e. power) lost to convection. Radiation which intercepts the filament after emission can only be reflected diffusely. This process is illustrated in Fig. 5.14 with the initial emission shown in Fig. 5.14a and the interception between a ray and a filament shown in Fig. 5.14b.

A distinction must be made, however, between the radiative efficiency of the lamp and the radiative efficiency of the filament. The radiative efficiency of the lamp takes into account the effect of the quartz envelope absorption and therefore if used here will result in underestimation of the overall reflector efficiency due to the double-accounting of quartz absorption. Therefore, the numerical model developed in Chapter 3 was used to estimate the filament radiative efficiency, which results in marginally higher values. The lamp radiative efficiency and the filament radiative efficiency are compared in Fig. 5.15.

In the 2D model, the filament is defined using a rectangular profile, as shown in Fig. 5.16. Intersection with the filament can be determined by testing intersections with the four lines which compose the filament boundary. If it is determined that the ray intersects with the filament, the ray will be diffusely reflected, and therefore the normal vector at that location is required. The normal vector for each intercept location is shown in Fig. 5.16b.

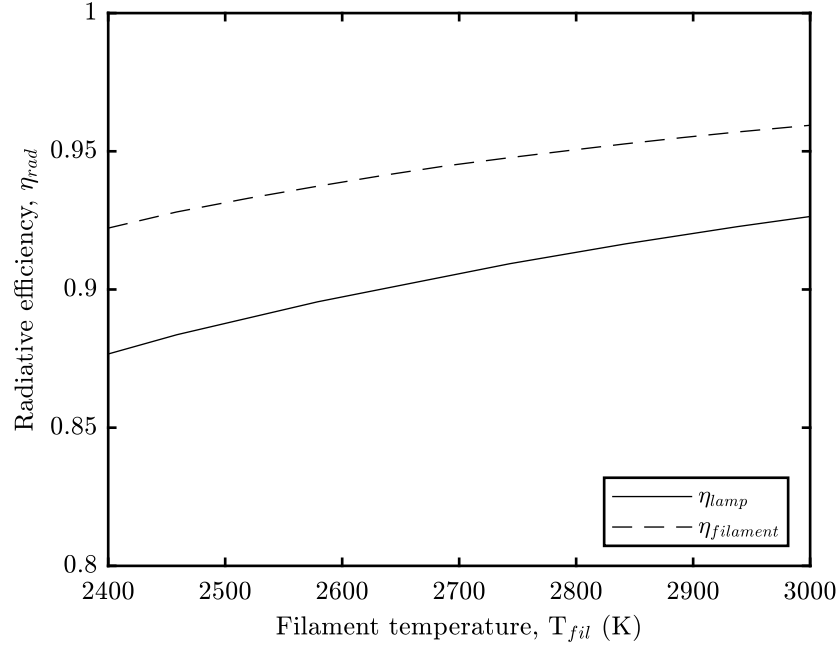


Figure 5.15: Lamp and filament radiative efficiency for the 1000 W QTH source.

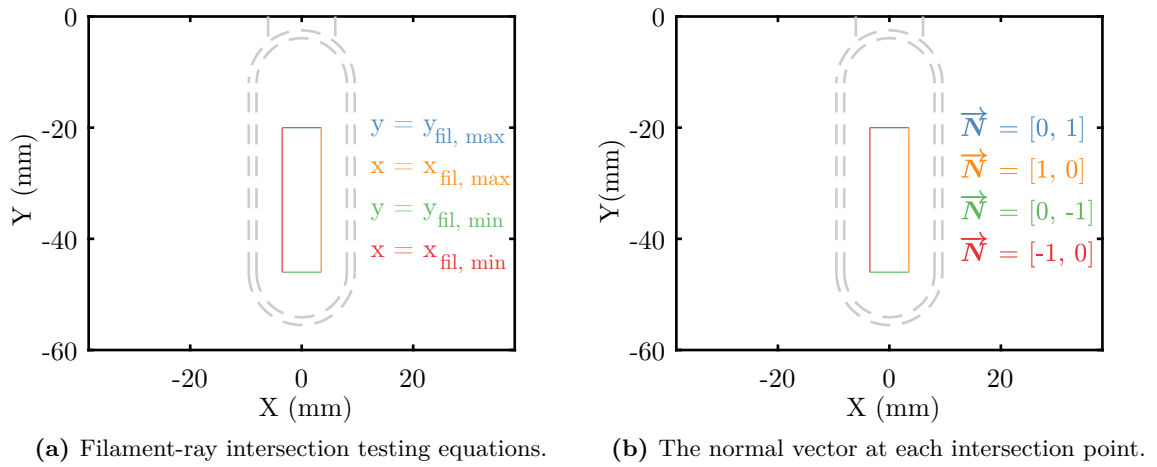


Figure 5.16: Illustration of the filament construction.

5.5.5 Tracing within the quartz bulk

If the ray enters the quartz envelope, one must turn their attention to the theory of radiation within participating media. A general overview of the governing equations and the use of MCRT for participating media can be found in chapters 10 and 21 of reference [25]. To broadly summarise, participating media may reduce the intensity in the direction of travel by absorption and scattering, which are defined by the absorption coefficient (κ) and the scattering coefficient ($\sigma_{s\eta}$) respectively. Re-emission from the bulk material can also be considered. For the quartz envelope, the problem is relatively simple since the material is homogenous with few impurities, and thus scattering can be ignored. Furthermore, it was previously assumed that re-emission from the quartz can be neglected. Consequently, it is necessary to only take absorption into account in the model. The flowchart shown in Fig. 5.17 illustrates the main steps undertaken by the MCRT during ray propagation within the quartz envelope.

The intersection tests are performed by using the techniques already outlined in this section (equations of a line and the equation of a circle) for the quartz interfaces. Once the new intersection point within the quartz has been determined, the likelihood of absorption within the quartz must be considered. The probability of absorption can be determined using the following equation [51]:

$$\alpha = 1 - e^{\frac{-4\pi\kappa s}{\lambda}} \quad (5.19)$$

Here s is the distance travelled by the ray through the quartz. Similarly, this is compared to a random number, and if the random number is less than the absorptivity, the ray is considered absorbed by the quartz.

If the ray is not absorbed, the Fresnel equations are again employed at the interface, with total internal reflection now a possibility. The surface normal vector at the interception location is used to determine the new direction vector based on either reflection or transmission through the interface. The quartz interfaces are assumed optically smooth, and therefore, all transmission and reflections through quartz interfaces are specular in this implementation.

5.5.6 Tracing outside the lamp

Outside of the lamp, the ray can intercept four bodies:

1. The quartz envelope.

2. The target surface.
3. The top surface of the reflector.
4. The curved reflector surface defined by the Bézier curve.

Tracing is initialised in the order listed, and if there is no valid intersection(s) with the quartz envelope, RT outside the quartz can commence. Fig. 5.18 depicts a flowchart

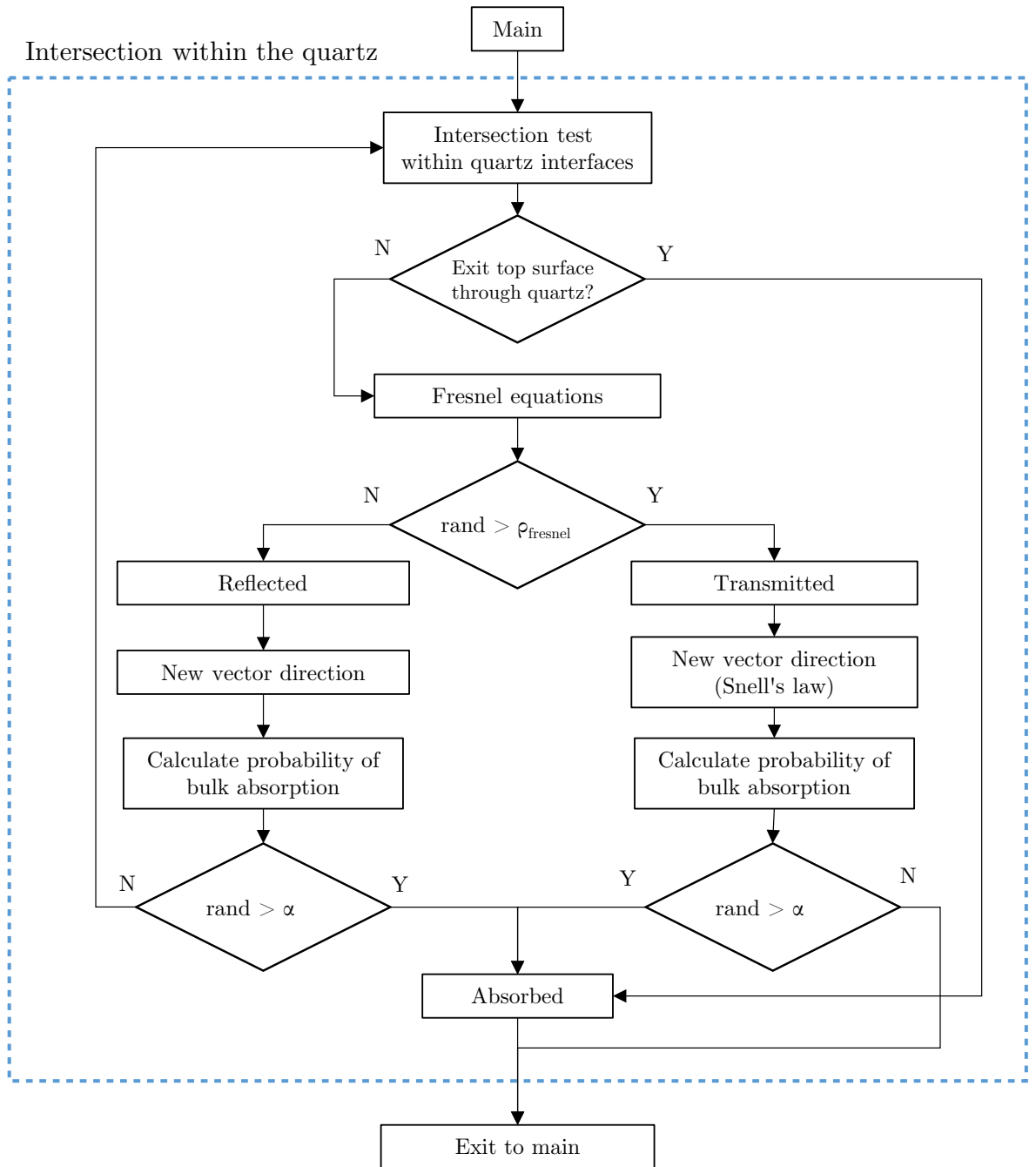


Figure 5.17: Flowchart of the subroutine for a ray propagating inside of the quartz bulk.

describing this process.

5.5.6.1 Reflection on opaque surfaces

Intersection with an opaque surface can result in only reflection and absorption, as described previously. If the algorithm determines that the ray will be reflected, the normal vector at that intercept location and the new vector direction must be determined. The process of determining the intercept position and the normal vector depends on the feature that the ray intersects, which can be broken down into the three possibilities:

Reflector exit: If the Y-vector is negative, an intersection test is performed with the target surface. This is achieved by substituting the y-position of the target surface into the equation of ray (Eq. 5.4) which is then solved for the x-value. An example of this process is shown in Fig. 5.19a after the ray has passed through the quartz envelope where the intersection is tested with a horizontal plane located at -90 mm. If this x-value is within the maximum width of the target surface, it is deemed to intersect this surface and exit the reflector. In the case of when the ray exits the reflector, the normal vector does not need to be calculated as the tracing of that particular ray has concluded. If the ray intersects outside of the limits of the target surface, an intersection test is then performed with the Bézier curve.

The top surface of the reflector: Intersection with the upper surface in which the lamp is inserted into the reflector is tested if the y-vector is positive. The intersection test can be performed using a method similar to the target surface. In this case, the y-value of the top surface (which in the case of this model is fixed at zero) is substituted into the equation of a ray which is then solved. An example of this is shown in Fig. 5.19b. If the intersection is outside the limits of the top surface of the reflector, the model proceeds to the testing of intersection with the Bézier curve. Since this surface is horizontal, the ray will always intersect from below the surface, and the 2D normal vector is consequently $[0 \ -1]$.

Bézier curve intersection: The solution to the intersection with a Bézier curve can be determined using several methods. A description of these methods requires detailed discussion and therefore, will be explained separately in section 5.5.8.

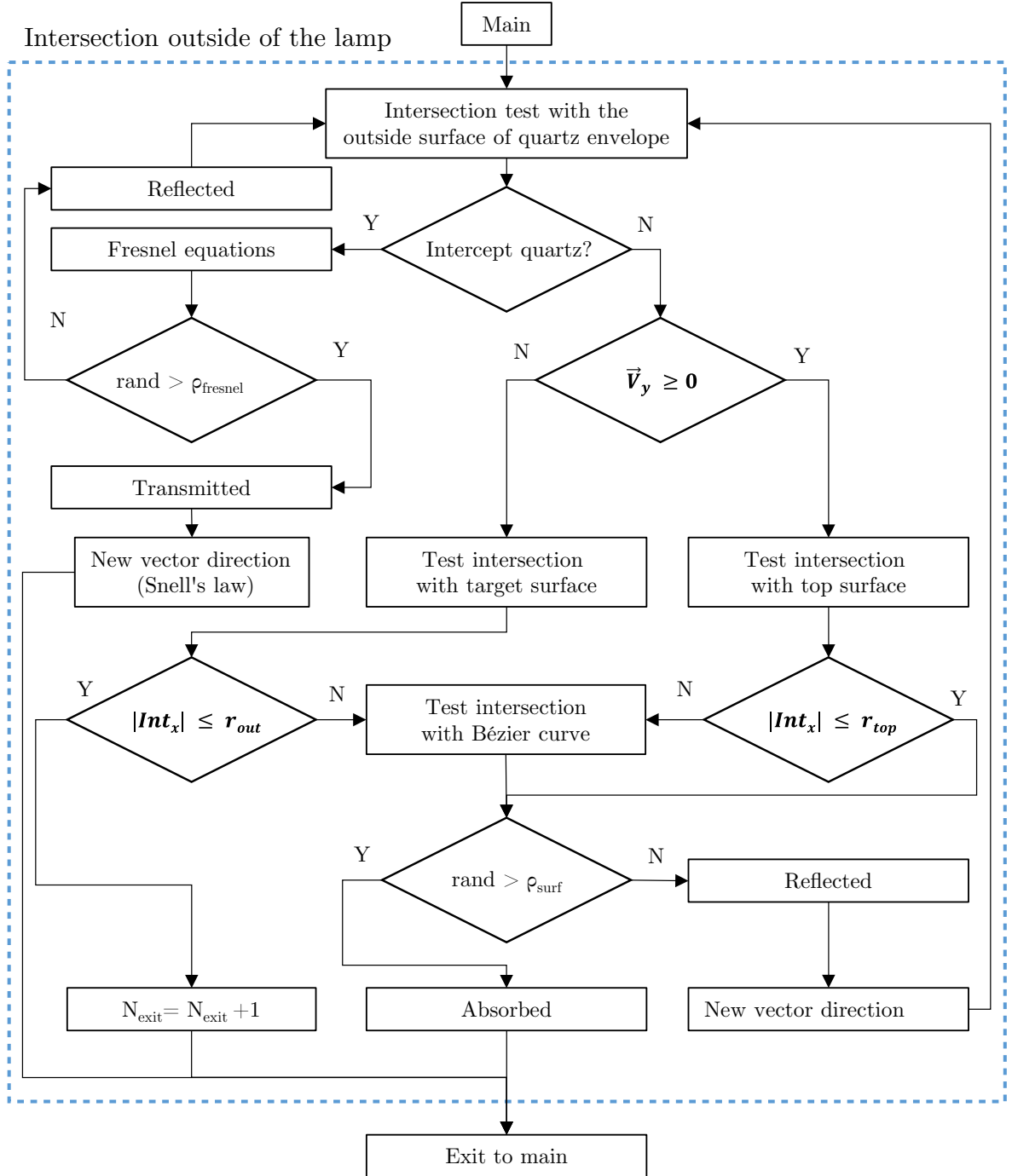


Figure 5.18: Flowchart of the subroutine for a ray propagating outside of the quartz envelope.

5.5.6.2 New direction vector

Once the intersection point and the normal vector have been determined, the new direction vector can be found using Snell's law of reflection for the specular case (Eq. 5.18). For a diffuse reflection, Lambert's cosine law is used similar to a case for the initial emission of radiation (Eq. 5.5). When the new intersection point and the vector direction have been

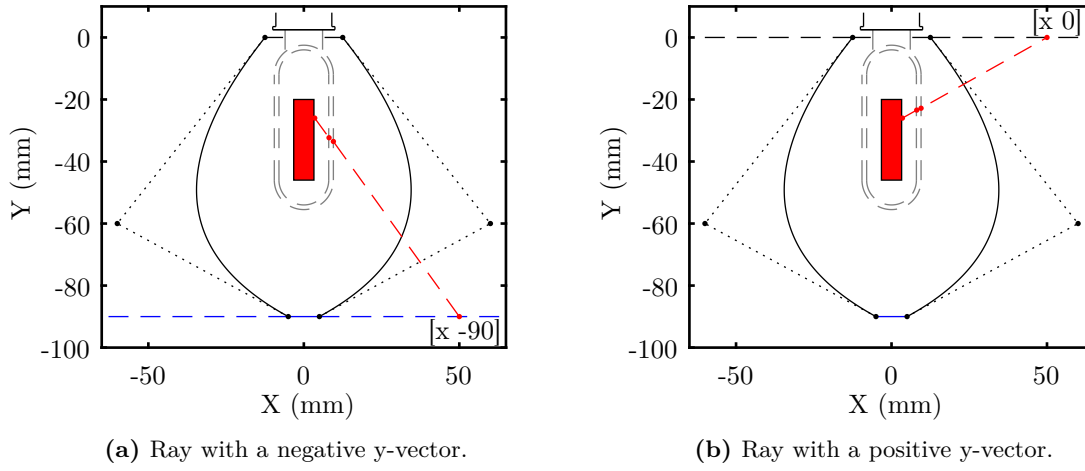


Figure 5.19: Intersection testing process outside of the quartz envelope.

determined, the model can progress onto calculating the next intersection point.

5.5.7 Determine efficiency

After each ray has either been absorbed or exited the reflector, the ray tracing algorithm concludes. The efficiency calculation is performed by simply finding the ratio between the total number of rays and the number of rays which exit the reflector:

$$\eta_{ref} = \frac{N_{exit}}{N_{total}} \quad (5.20)$$

5.5.8 Bézier-ray intersection algorithms

Unfortunately, there is no analytical solution to the problem of a ray intersecting with a Bézier curve, and therefore, alternative methods have to be explored. Two potential techniques can be used as described in the literature:

1. Numerical methods to solve the intersection without any simplifications.
2. Bézier subdivision which systematically reduces the curvature of the Bézier curve such that it can then be assumed to be a line after a specified tolerance is reached.

5.5.8.1 Numerical methods

Determining an intersection numerically can be achieved by simultaneously solving the equations of the Bézier curve and the equation of the ray. The equation of a ray when broken

down into its components can be written as:

$$R_x(t) = P_x + t_R \times \vec{v}_x; \quad R_y(t) = P_y + t_R \times \vec{v}_y \quad (5.21)$$

Where R is the new position, which is a function of the parametric variable t , P which is the current or known position along the ray, and $\vec{v}$, which is the vector direction. The equation of the quadratic Bézier curve is:

$$Q(t_B) = (1 - t_B)^2 P_0 + 2t_B(1 - t_B)P_1 + t_B^2 P_2 \quad (5.22)$$

Which can also be decomposed into the X and Y components. The intersection can then be found by simultaneously solving the following equations:

$$Q_x(t_B) - R_x(t_R) = 0; \quad Q_y(t_B) - R_y(t_R) = 0; \quad (5.23)$$

The surface normal vector at the intercept location can be found by substituting the intercept location into the differentiated Bézier curve equation.

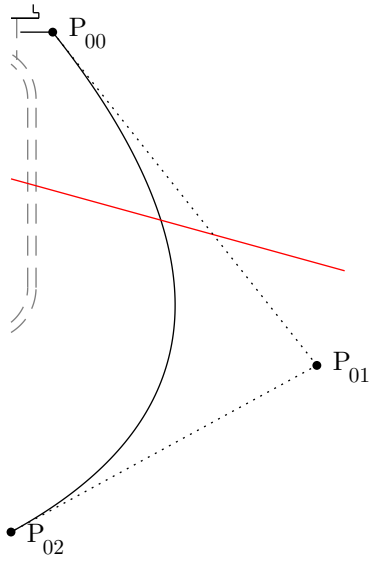
5.5.8.2 Bézier subdivision

Finding the intersection point between a ray and a Bézier curve can also be achieved using subdivision. This process involves continuously dividing the curve using De Casteljau's algorithm until the curvature can be considered negligible [155]. The "curve" can be assumed to be a line, and a trivial ray-line intersection test can then be performed. The implementation of Bézier subdivision for a range of curve orders can be found in the work of Barsky [156]. The process is illustrated in Fig. 5.20 and described in the following paragraphs for the case of a quadratic curve.

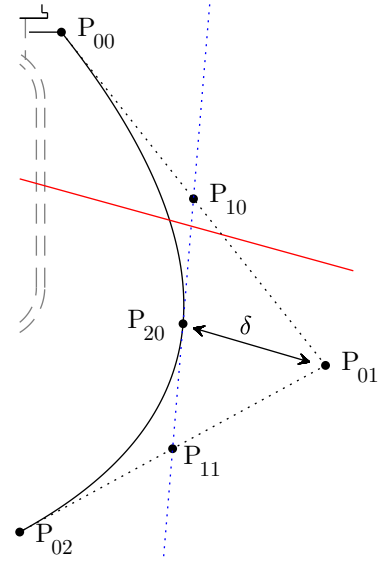
First, the Bézier curve is defined using the three control points P_{00} , P_{01} , and P_{02} , as shown in Fig. 5.20a. Then the interpolating polygon control points P_{10} , P_{11} and P_{20} can be determined as shown in Fig. 5.20b using the following equations:

$$P_{10} = \frac{P_{00} + P_{01}}{2}, \quad P_{11} = \frac{P_{01} + P_{02}}{2}, \quad P_{20} = \frac{P_{10} + P_{11}}{2} \quad (5.24)$$

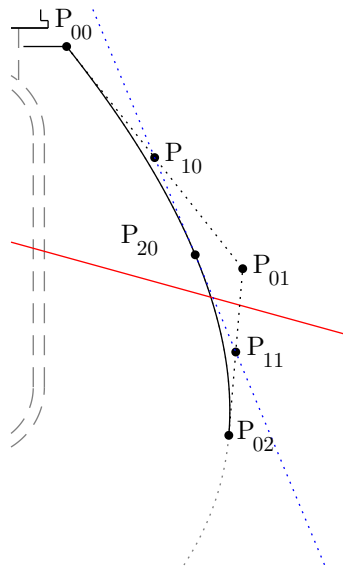
After calculation of these three points, an intersection test with the line which is tangent to the Bézier curve which passes through point P_{10} , P_{11} , and P_{20} is then carried out. If the



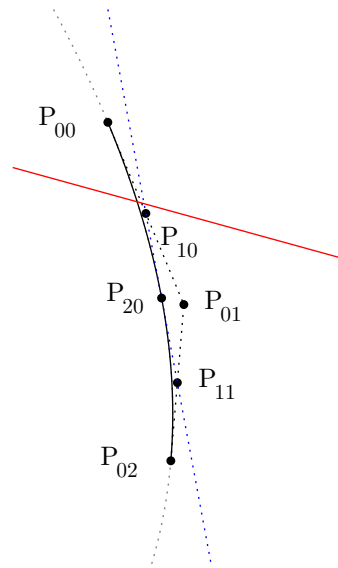
(a) A ray intersecting a Bézier curve.



(b) Determine the secondary control polygon points.



(c) Subdividing the curve by half based on the intercept location.



(d) Subdividing of the curve a second time.

Figure 5.20: Bézier subdivision for a quadratic curve.

value of the y-intersection with this line is greater than the value of the Y_{21} , the curve is subdivided towards the top half of the curve from the perspective shown in Fig. 5.20b to c.

The new control points can be determined as:

$$B_{sub} = [P_{00}, P_{10}, P_{20}] \quad (5.25)$$

This allows the curve to be split in half while maintaining the same shape and position for the remaining section. The new interpolating polygon points are then calculated, and the curve is subdivided again. In this case, the value of y-intersection is less than the value of the Y_{21} , the curve is subdivided towards the bottom half of the curve, as shown in Fig. 5.20c to d. The new control points are:

$$B_{sub} = [P_{20}, P_{11}, P_{02}] \quad (5.26)$$

Throughout this process, the curvature of the Bézier curve is measured by the distance between the P_{21} and P_{02} :

$$\delta = \sqrt{(X_{20} - X_{01})^2 + (Y_{20} - Y_{01})^2} \quad (5.27)$$

The subdivision process is repeated until a specified curvature tolerance is achieved, which in the case of this work was set as 10^{-6} mm. This typically resulted in 8-15 subdivisions for each intersection test, depending on the local level of curvature at the intercept point. Once the curvature of the Bézier curve section has been reduced to a line, the normal vector is determined by the vector direction perpendicular to this line.

Bézier subdivision was found to be at least two orders of magnitude faster than solving the problem numerically without any significant compromise in the accuracy of the solution, and therefore, this method will be employed going forward in this work.

The performance of the custom IR reflector developed will be compared to that of the performance of an optimised ellipse in the remaining sections of this chapter and throughout Chapter 6. Hence, an ellipse intersection algorithm was also developed, which is detailed in Appendix C.3.1.

5.6 MCRT model validation

5.6.1 Comparison to an ellipse with a point source

The ray tracing algorithms developed for the Bézier curve and ellipse can be validated by simulating a point source placed at the focal point (F_1) of a 100 mm major 50 mm minor axis length semiellipse. If simulated correctly, the radiation that intercepts the reflector surface will be directed onto the second focal point (F_2). The setup for this validation is shown in Fig. 5.21a. This ensures that the intersection and vector direction calculations are implemented correctly. The ellipse is centred at the origin, and thus the two focal points are located at $[0, 86.6]$ and $[0, -86.6]$. The Bézier-ray intercept algorithm must be tested with a Bézier curve, and therefore a cubic Bézier curve was matched to the elliptical section by using a GA to find the most suitable control points. Good agreement between the ellipse and Bézier curve was established with only minor differences across the entire length.

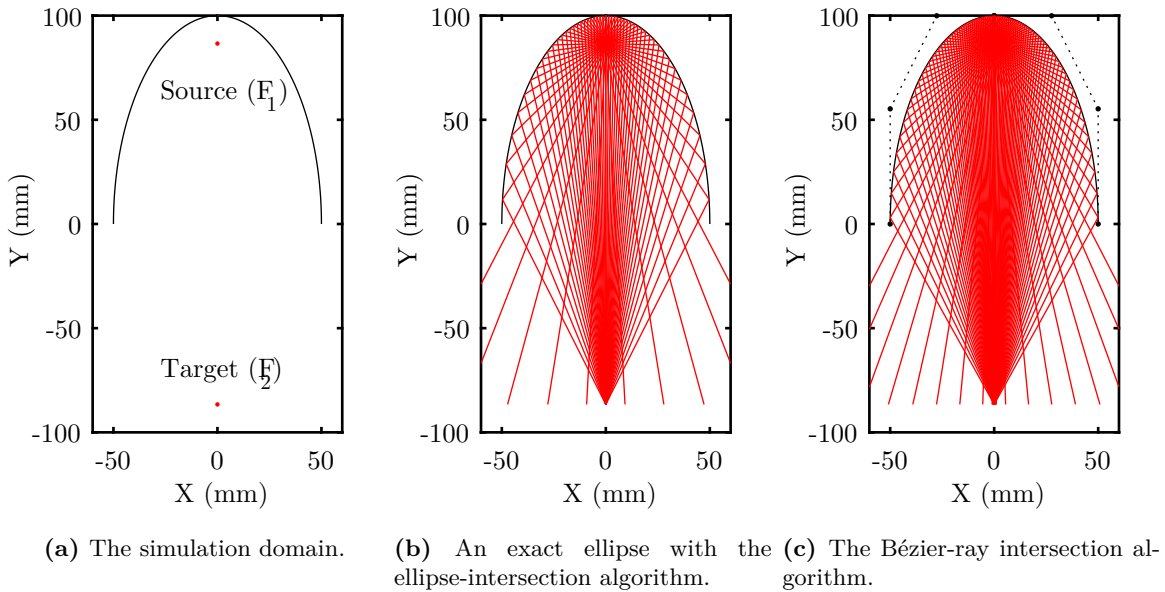


Figure 5.21: Comparison between the Bézier curve and ellipse intersection algorithm for a 100 mm major and 50 mm minor axis length with 100 rays.

As shown in Fig. 5.21b and c, both algorithms correctly predict that radiation emitted from F_1 will be focused at F_2 . For a theoretically perfect ellipse, radiation which intercepts the reflector will be directed towards the focal point at $[0, -86.6]$ with no error. The average ray deviation from the centre point at this point was 1.3×10^{-13} mm for the elliptical code, whereas for the Bézier subdivision algorithm it was greater, yet still relatively small at an

average value of 0.18 mm. This can be observed in Fig. 5.21b where there is no apparent focal width visible at the scale shown for the ray-ellipse intersection code, whereas in Fig. 5.21c, there is a small but noticeable focal width.

The error associated with the ray-Bézier intercept algorithm is not due to the subdivision tolerance, as decreasing the tolerance did not reduce the error. It is therefore considered to be a function of the Bézier fit with the ellipse. It is concluded that both algorithms find the intersection ray and new vector direction with sufficient accuracy to be utilised in this work.

5.6.2 Validation of the quartz transmissivity

The absorption properties of the quartz material heavily influence the overall performance of the FIRH, especially since the radiation may pass through the quartz envelope several times on the path to the reflector exit. Validation was performed by determining the transmission of a series of rays through quartz at a normal incident angle. A quartz thickness of 0.953 cm is used to allow comparison to the work of *Beder et al.* [157]. Both bulk absorption in the quartz and Fresnel reflection losses are taken into account. The maximum transmissivity is approximately 94% due to Fresnel reflection losses. The samples tested by *Beder et al.* show slightly different absorption properties in the 2.5-4 μm wavelength range, as shown in Fig. 5.22. However, good agreement is demonstrated in the visible and NIR wavelength ranges where the majority of the radiation will be emitted from the QTH source. The discrepancy at higher wavelengths may be attributed to differences in the absorptivity of the quartz employed in the study of Beder compared to the data employed in this study.

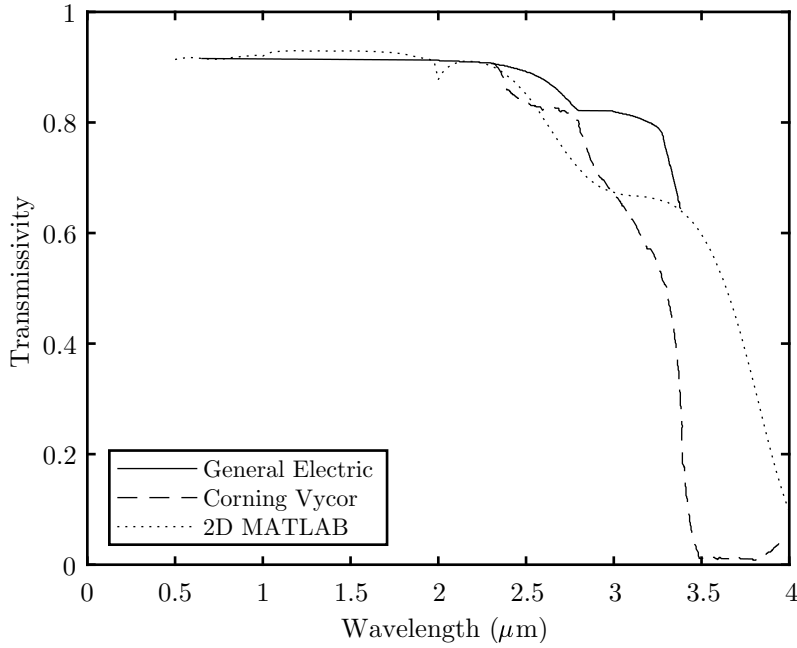


Figure 5.22: Quartz transmissivity comparison MCRT prediction and *Beder et al.* [157] for a 0.985 cm thick sample.

5.7 Genetic algorithm implementation

The GA employed in this work is part of the MATLAB optimisation toolbox. The details of the implementation can be found by consultation of the MATLAB documentation [158]. General guidelines and information on the use of GAs can be found in reference [159]. Several settings which are important to the performance of a GA are discussed briefly in this section.

5.7.1 Mutation

The mutation rate defines how often random variations occur within the genes of the candidate solutions during the formation of the subsequent generation. Mutation diversifies the population and allows the discovery of solutions which were not initially part of the gene pool. Hence, the process of mutation is critical to the success of a GA. However, if the mutation rate is too high, the algorithm will begin to resemble a random search and will find difficulty converging on a final solution.

5.7.2 Crossover

The two settings that control the crossover of the GA are the crossover fraction and the crossover function. The crossover rate or fraction comprises the balance of the mutation

rate, i.e. offspring can either be created through mutation or crossover. The crossover options define how parents combine to produce offspring and create a new candidate solution. Crossover spreads high-performing solutions to the posed problem throughout the gene pool and aids with the convergence of the population towards a single optimised solution.

5.7.3 Elitism

Elitism is a feature which promotes the passing of high-performing or ‘elite’ solutions into the next generation without the need for crossover or mutation. Elitism has a significant impact on the efficacy of the optimisation process by preventing the loss of high-performing solutions. However, if the elite count is too high, the solution may tend to converge on a suboptimal solution discovered early in the optimisation process.

5.7.4 Population size

GAs are semistochastic methods meaning they rely on random number generation to converge on optimal solutions. As a result, the same path will not be traversed with each optimisation sequence. Consequently, the algorithm should be run with the largest population size possible to ensure that variation is reduced. However, a larger population requires more evaluations and hence must be balanced with the available computational resources.

5.7.5 Performance considerations

One of the main drawbacks of a genetic algorithm is that it will often retest the same locations in the solution space. This is addressed in the implementation of the GA by storing the results in a database, and by checking the database before computation to determine if the particular computation has been performed previously. If so the value is retrieved from the database instead of running the simulation again. This drastically increases the computational efficiency of the GA, particularly towards the latter parts of the process where the optimisation is focused on a small area of the solution domain.

5.8 Conclusion

The development of a 2D MCRT model which can be used to optimise a FIRH has been outlined in this chapter. The following conclusions can be drawn from this section of the work.

The optomechanical design procedure was outlined which involves using a GA to heuristically search the solution domain, a Bézier curve to parameterise the shape of the reflector, and a MCRT model to determine the efficiency of each reflector shape. The MC method is employed due to the advantages this method delivers when dealing with complex radiative heat transfer problems in terms of simplicity, robustness, and the lack of correlation of the computation time with the complexity of the problem.

The model developed required several simplifying assumptions but takes account of the important physical processes which drive the heat exchange within the reflector enclosure. The methods employed for finding the intersection with the lamp components are outlined using a combination of primitive geometric shapes. The tracing algorithm divides the modelling domain into three locations of the internal volume of the quartz envelope, the bulk of the quartz envelope, and the volume outside of the quartz within the reflector geometry. The subroutines for each of these locations were outlined and discussed. The reflector shape is defined using a Bézier curve, and the methods for determining an intersection between the ray and the curve are detailed with Bézier subdivision delivering improved performance over numerical methods.

Chapter 6

FIRH design and characterisation

6.1 Introduction

This chapter will describe the design output from the 2D FIRH optimisation process developed in Chapter 5. The difficulties associated with the use of ellipses for the focusing of radiation from an extended QTH source are first detailed. Next, the design considerations regarding the manufacture of the optimised reflector shape will be outlined and discussed, including assembly considerations, the mounting of the lamp within the reflector enclosure, and the cooling of the reflector. Finally, the reflector will be characterised with regard to the power output, startup time, filament temperature, reflector body temperature, and light recycling. Adjusted theoretical limits for this FIRH are outlined based on the rate of light recycling and the associated enhancement of the radiance of the QTH source.

6.2 Elliptical reflectors: suitability for use with extended sources

As discussed in this work previously, there are numerous issues regarding the use of ellipses to focus radiation when using a real, nonpoint, IR source. Fig. 6.1 shows the setup of the 100 mm major axis 50 mm minor axis ellipse, which can be employed to focus radiation emitted from a source (F_1) towards the second focal point (F_2).

The overarching issue inherent to focusing IR radiation is that the sources available on the market cannot be classified as point sources or even resemble a small sphere. Most commercially available IR sources employ coiled or double-coiled tungsten filaments that take the form of a single cylinder or banks of cylinders arranged in a cuboid shape. This geometry severely limits the ability to efficiently focus radiation onto a small area for any reflector size and shape, but particularly for an ellipse that is not explicitly designed to focus radiation from an asymmetric source.

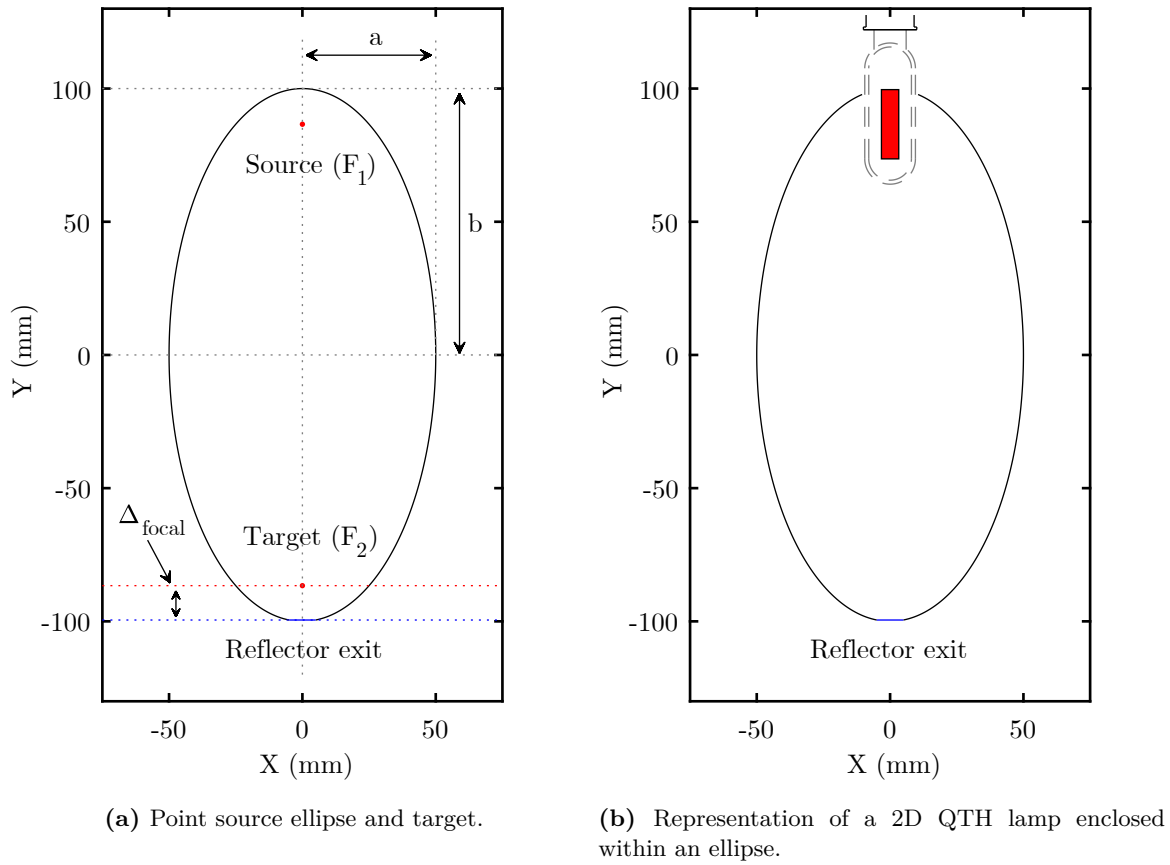


Figure 6.1: Simulation domain setup for elliptical tests with a minor and major axis lengths of $a = 50$ mm, and $b = 100$ mm respectively. The sources are shown in red and reflector exits are shown in blue.

The second issue is that the height of the focal plane (F_2) and the height of the exit plane do not match when a small exit is employed, as shown in Fig. 6.1a. This implies that the exit must be enlarged to align the focal plane and the exit plane, or the rays intercepting the focal plane may not reach the reflector exit. Conversely, the focal point (F_1) is often too close to the wall of the ellipse to allow the geometric centre of the filament to be located on the focal point of the ellipse while ensuring the entire filament is housed within the enclosure. This issue is highlighted in Fig. 6.1b, where a portion of the filament protrudes from the reflector inlet orifice. This will be exacerbated with smaller ellipse sizes.

Even if the filament is a suitable size to be entirely accepted into the reflector, the quartz envelope will have to pass through the wall of the enclosure. Hence, the lamp insertion inlet will be slightly larger than the quartz envelope, which will result in an orifice many times the diameter of the emitting source.

Some of the issues above can be addressed by enlarging the ellipse relative to the size of the lamp. This will move the focal point away from the wall allowing the entire filament to be located inside the reflector. However, a large reflector is undesirable for many reasons, such as the cost of manufacture and finishing, and the size limitations which accompany many focused IR applications.

6.2.1 Optimal elliptical shape

An optimal ellipse geometry must be found for the 1000 W source to determine the performance limitations of an ellipse and allow a comparison to the optimised Bézier shape developed later in this work. Since there are only two variables to be optimised, the problem can be solved by a parametric investigation of the solution domain. The ellipse was specified to have a 10 mm outlet and a 21 mm diameter inlet orifice, and the geometric centre of the filament was located at the focal point of the ellipse.

A 2D efficiency map of the solution domain is shown in Fig. 6.2 with the reflector major axis length on the x-axis and the normalised minor axis length on the y-axis. The maximum efficiency found for this setup was 21% by an ellipse that has a total length and width of 420 mm and 156 mm respectively. As shown on the map, the efficiency tends to increase with reflector length and decrease with minor axis ratio, which is due to the combination of the effects already discussed plus the complex interaction of the radiation with the quartz envelope and filament.

There are areas of low efficiency in the top right and bottom left-hand corner of the 2D

map because of the constraints placed on the system. For the top right-hand corner, a limit is placed on how far the lamp can be inserted into the reflector since the metallic surfaces of the lamp need to be protected from the radiation or risk overheating. For the bottom left corner of the graph, the efficiency is also low as a large proportion of the filament is located outside of the reflector in order to satisfy the constraint that the geometric centre of the filament is placed on the focal point of the ellipse.

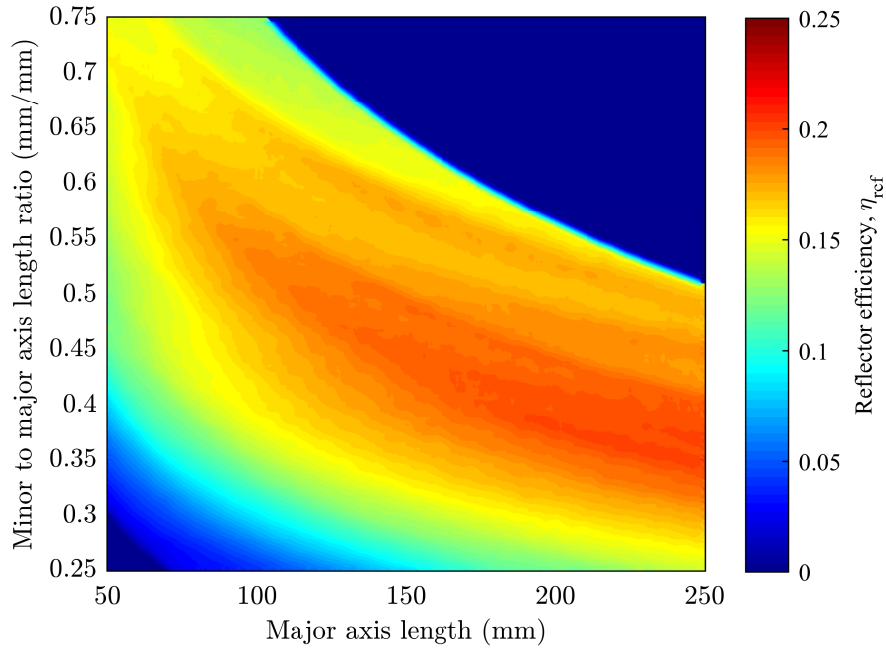


Figure 6.2: The ellipse efficiency solution domain for the 1000 W QTH lamp with 10,000 rays per simulation and a 250×250 simulation grid.

Although this process delivered reasonable results and an optimised ellipse was found, the optimisation of this shape is severely limited since an ellipse is constrained to changes of only the overall length and width of the reflector. Improved results will be garnered by employing a more flexible definition of the reflector shape, which can allow the placement of the lamp in a more suitable position and the design of a bespoke holder around this lamp to increase the reflective surface area within the enclosure.

6.3 Optimisation of a Bézier shape

Along with the selection of the source, one of the first steps in the design of a FIRH is to specify the outlet diameter. For context, the SpotIR heater manufactured by PCS has a 14 mm diameter outlet, while the units produced by Thermo Riko use a 20 mm diameter outlet. Other devices listed in Table 2.1 on page 38 have outlet or spot sizes ranging between 3 and 24 mm.

6.3.1 Selection of an outlet size

As described in section 2.4.2, there is a trade-off between the efficiency and heat flux output of a FIRH, with smaller outlet sizes tending to deliver higher heat fluxes and lower efficiencies. Conversely, increasing the exit size leads to higher efficiencies and lower heat fluxes. For the FIRH being developed, one should choose an outlet size such that it is useful not only for soldering applications but for processes such as metal annealing, high-temperature testing, and polymer welding. Soldering requires small outlet sizes to allow radiation to be directed over a small target, whereas processes such as metal annealing and sample heating would preferably have larger outlets to allow faster processing times.

The selection of an outlet size for a FIRH is an aspect which has not yet been addressed in the literature explicitly. For the design of reflectors which aim to maximise the efficiency of the radiation transfer between a source and a target, étendue and skewness-optimised reflectors can be designed (see Fig. 2.26 on page 51 and the related discussion). Designing a reflector only for efficient radiation transfer will result in larger exits than employed in typical FIRH devices, and consequently, lower heat flux outputs. Since the goal of this research is to improve the heat flux performance of these devices so that they can be used in a spectrum of applications that necessitate high intensities, this option can be disregarded.

Besides designing for étendue or skewness discrepancies between the source and target, there is no other approach detailed for specifying an outlet size for a specific heat flux or efficiency requirement. Therefore, the outlet size of this FIRH was selected as 10 mm such that it is near the median of the outlets of the FIRHs discussed so far and is also suitable for a range of applications including cold spray (i.e. metal heat treatment) which produces coating tracks of width 6-10 mm.

It is noted that the methodology used to specify the outlet is not satisfactory. For applications where there is no need for a specific outlet size, it is still unclear what outlet

to choose to meet a given efficiency and heat flux requirement. Furthermore, it is apparent that due to the effects of étendue or skewness differences between the source and target, the outlet size should be chosen while somehow taking into account the geometry of the source. This aspect of focused IR design will be a primary focus later in this work.

6.3.2 Specification of reflector size limits

An illustration of the simulation domain and the Bézier control point limits for the optimisation process is shown in Fig. 6.3. The limits of the reflector size for the optimisation are specified as follows:

1. The X_0 and Y_0 coordinates associated with P_0 are fixed at a position of $[12.5, 0]$. The Y coordinate is set for simplicity to zero, and the X coordinate is set based on the size of the quartz envelope.
2. The X_1 and Y_1 coordinates of P_1 are free to move in any direction between the limits of $X_1 \in [25, 100]$ and $Y_1 \in [-100, 0]$. The minimum dimension of 25 mm for the X_1 is chosen to ensure that the walls of the reflector cannot intersect with the lamp. The lower limit is chosen as slightly greater than the limits of the overall Bézier length, which removes unfeasible portions of the domain from the search space where both points are located near the lower limit.
3. X_2 is fixed at a position of 5 mm to provide a 10 mm diameter outlet, and Y_2 is free to move within the limits of $Y_2 \in [-120, -70]$ to ensure a small reflector length.
4. A linear constraint is placed on the system such that $Y_2 < Y_1$ to prevent tracing of invalid shapes. If $Y_2 < Y_1$, the efficiency of the reflector is returned as 0% before tracing.

A custom reflector, designed explicitly for the lamp size and shape, allows the position of the filament to be fixed inside the reflector body before the optimisation process begins. This will allow the manufacture of a holder that tightly fits around the narrowest part of the lamp (i.e. quartz the base), allowing the reflective area to be maximised within the reflector enclosure. The filament is shown in red and is located 33.5 mm from the P_0 as measured from its geometric centre.

The simulation domain is also shown in Fig. 6.3 with the three Bézier points defining the Bézier curve, the outline of the quartz envelope is shown in the grey dashed line, the

filament is shown in red, and the exit is shown in blue. The limits for P_1 and P_2 are also shown as dotted lines. The lamp inlet orifice diameter is set such that the cross-sectional area is equivalent to the square profile of the quartz base. For this lamp, the base measures 19 mm x 6 mm which equates to a diameter of ~ 12 mm.

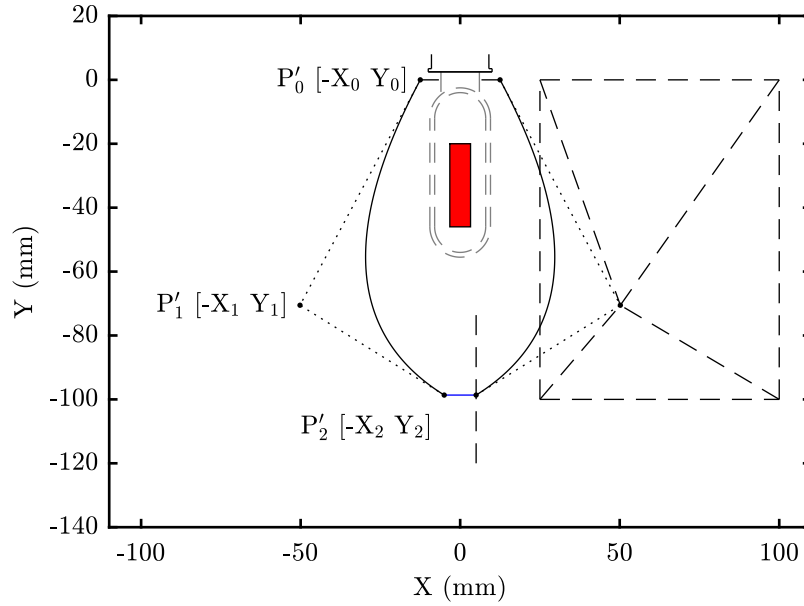


Figure 6.3: The simulation domain for the 2D model with the filament shown in red, the exit in blue, the quartz in grey dashed lines, and an example Bézier curve shown in black. The bounds for P_1 and P_2 are also illustrated with dashed lines.

6.3.3 Manufacturing considerations and limitations

The design of a reflector shape inherently must consider the manufacturing techniques to be employed and the associated limitations of these processes. The use of traditional subtractive techniques (such as milling or turning) will limit the range of reflector shapes that can be fabricated. For example, the machining of both steep and flat surfaces during a single process can be problematic while using a standard 3-axis milling setup. This is illustrated in Fig. 6.4 which shows the 2D profile of a potential reflector shape. The angle between the two endpoints of the Bézier curve and the horizontal plane are shown as θ_1 and θ_2 and will be steepest angles in this concave reflector shape. As the angle of the surface being machined approaches 90° to the horizontal (i.e. when machining a near-vertical wall), large scallops of material will be produced resulting in a poor surface finish and low dimensional accuracy. Therefore, the steepness of the slope of the reflector wall may need to be constrained in the

absence of more sophisticated setup, such as a 5-axis milling machine.

Constraining the steepness of the reflector wall can be implemented trivially during the optimisation process by determining the maximum slope of the reflector near both endpoints, as illustrated in Fig. 6.4. If the slope of the surface exceeds a specified angle, the shape can be discarded during the GA optimisation process. For the range of shapes produced by optimisation of the quadratic Bézier curve, the maximum slope of the reflector wall was not deemed to be a limiting factor even for a 3-axis milling machine; therefore, this did not need to be considered during the optimisation process for this particular shape type.

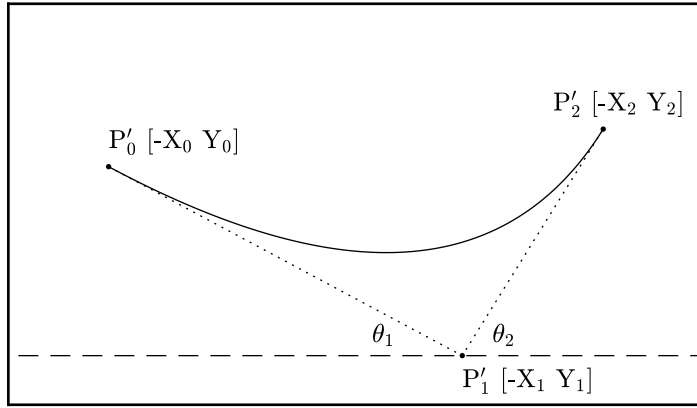


Figure 6.4: An illustration of the potential manufacturing constraints on the reflector profile. The steepest slopes of the concave reflector profile are shown as θ_1 and θ_2 .

The form, waviness, and surface roughness tolerance of the reflector can be specified to establish that the proposed manufacturing processes are suitable for producing the FIRH reflector shape. For a freeform surface, a tolerance band can be applied, which ensures that the final surface falls within a given distance from the nominal reflector surface. To determine if the specified tolerance is met, the form of the reflector surface can be measured using a CMM [160] or x-ray computed tomography [161]. Conversely, the measurement of the small scale waviness and roughness on the freeform surface will prove more challenging. In the experience of the author, the reflector is not particularly sensitive to the form and position of the reflector, with small changes in either resulting in little to no change in the predicted efficiency. One would anticipate that the performance of the reflector will be more sensitive to the waviness and roughness of the surface as this more strongly influences the direction that the radiation will propagate after reflecting on the surface.

The surface roughness of the freeform reflector surface will be affected by a range of

processing parameters such as the properties of the workpiece, tool geometry and wear, cutting parameters and cutting forces, and the milling strategy employed [162]. Importantly, there is a trade-off between manufacturing time and the surface finish of the reflector. The work of *Miko et al.* demonstrated a proportional relationship between the specified cusp height and the roughness of a milled surface [162]. The cusp height is the ridge formed by the passes of a ball nose cutter and is a function of the step size and cut depth, as illustrated in Fig. 6.5 where D is the tool diameter, D_{eff} is the effective tool diameter, w_{cut} is the cut width, d_{cut} is the cut depth, and h_{cusp} is the cusp height. Reducing the cusp height will therefore increase the machining duration and must be balanced with manufacturing costs and machine availability. This is a particularly important consideration for the mass production of these reflectors.

The reflector surface will need to be finished regardless of the parameters used as the machining process will typically produce a roughness of the same order of magnitude as the cut depth and width. According to Eq. 2.10 on page 18 the surface roughness required for a specular reflection regime will be at most 30 nm for incident radiation with a wavelength of $\sim 1 \mu\text{m}$. Hence, a process such as polishing, buffing, superfinishing strategies, or a combination thereof, will be required to improve the surface finish to an appropriate level [163].

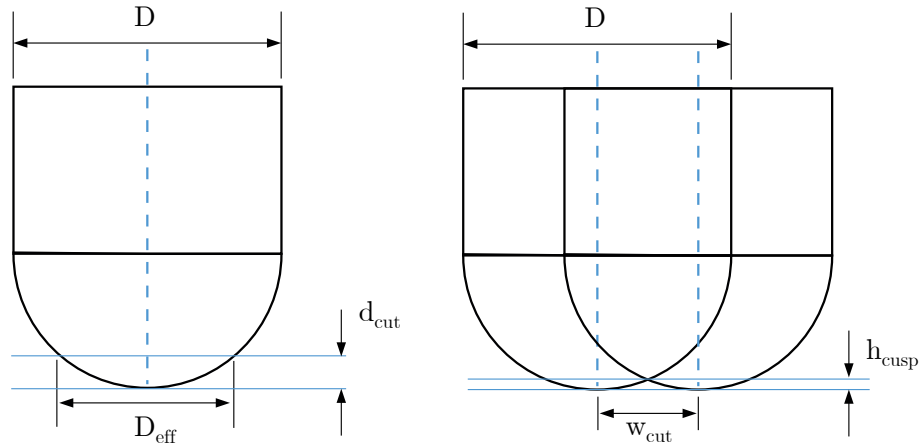


Figure 6.5: Cusp height and working diameter of a milled surface. Adapted from [162].

6.4 Optimised reflector shape

The reflector shape was developed using the optimisation process established in Chapter 5, by carrying out several optimisations using the GA with 1000 rays and a population size of 100 reflectors. An Au-coated reflector surface was assumed for all simulations in this 2D model. A larger number of rays were not used in this part of the study due to the computational cost of the simulations, which were deemed unnecessary for the prototype model. GAs should be optimised for each problem set being tackled in order to find the most appropriate operating parameters. This ensures that the GA does not converge too quickly or slowly and that the crossover and mutation functions preserve the important features of the reflector during the creation of the subsequent generations.

A thorough analysis of the GA settings is a substantial task due to the large number of parameters and potential settings for each. Therefore, for the prototype model, the default parameters employed in the MATLAB implementation will be used which are suitable for a wide range of problem types, albeit not optimal. The details of these settings can be found in Table 6.1. Optimised parameters for the GA for this problem type will be investigated in detail later in this work.

Table 6.1: GA settings used for the prototype model.

Migration direction	Population size	Fitness scaling function	Selection function	Elite count	Crossover fraction	Mutation function	Crossover function
Forward	100	Rank	Uniform	5%	0.8	Adaptive feasible	Scattered

From the list of optimal shapes that arose from these population sizes, the best was selected and used for the fabrication of the prototype reflector. The optimised shape is shown in Fig. 6.6. According to the 2D model, the optimal shape had a predicted efficiency of 25.8% when Au-coated. For the Al-reflector, the predicted efficiency is lower at 15.9%, highlighting the importance of the Au coating to the performance of the device. The final reflector was 89 mm long, and 76 mm wide which fits the requirement of a compact reflector that can be used in a range of applications.

Notably, this shape is quite different from that of an ellipse, which is designed specifically for a point source. This shape is instead optimised for the geometry of the lamp used in this reflector, and for that reason, delivers higher efficiency in comparison to an ellipse. The optimised Bézier shape, the best performing ellipse, and the most efficient of a smallest set

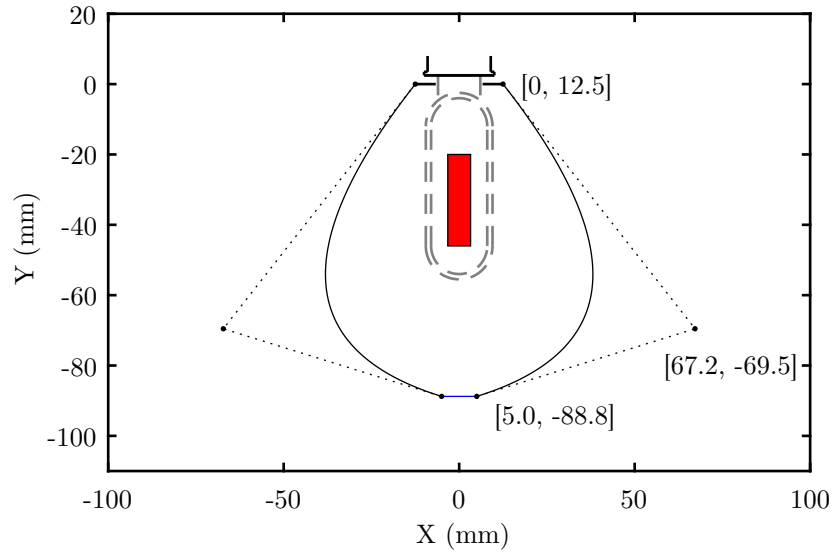


Figure 6.6: Optimised reflector shape for the 1000 W source.

of ellipses tested (100 mm reflector length) are compared in Fig. 6.7. The optimised shape is both smaller and more efficient than the ellipses for this source. The total length of the reflector is less than 90 mm in comparison to the large ellipse, which is over 400 mm long and delivers an efficiency of 21%. The smaller ellipse is 100 mm in length with a predicted efficiency of 12%. The efficiency is very low for the small ellipse as a large proportion of the filament protrudes from the entrance to the enclosure in order to satisfy the constraint that the filament's geometric centre is located on the focal point of the ellipse. The efficiency of this shape can be improved to 19% by adjusting the filament into the reflector by another 14 mm. However, this reflector efficiency is still far below that of the optimised shape. Conversely, adjustment of the filament position away from the focal point for the large optimised ellipse resulted in a decrease in the efficiency.

The measurement of reflector length and efficiency do not adequately quantify the difference between the scale of the reflectors: more importantly, the mass and volume of the device should be considered, which are proportional to the cube of length of the reflector (assuming the length increase is roughly proportional to an increase in the other dimensions). Hence, the optimal elliptical reflector would be of the order of ~ 64 times larger in terms of volume than the optimised Bézier curve. This would significantly increase the cost of material and manufacturing associated with the fabrication of the FIRH. The finishing of the surface of the reflector of the ideal ellipse to a sufficient roughness will be very time-consuming and costly.

Therefore, the optimised device demonstrates substantial improvements over the traditional FIRH designs in terms of efficiency, ease of manufacture, and potential to be employed in a wide range of applications.

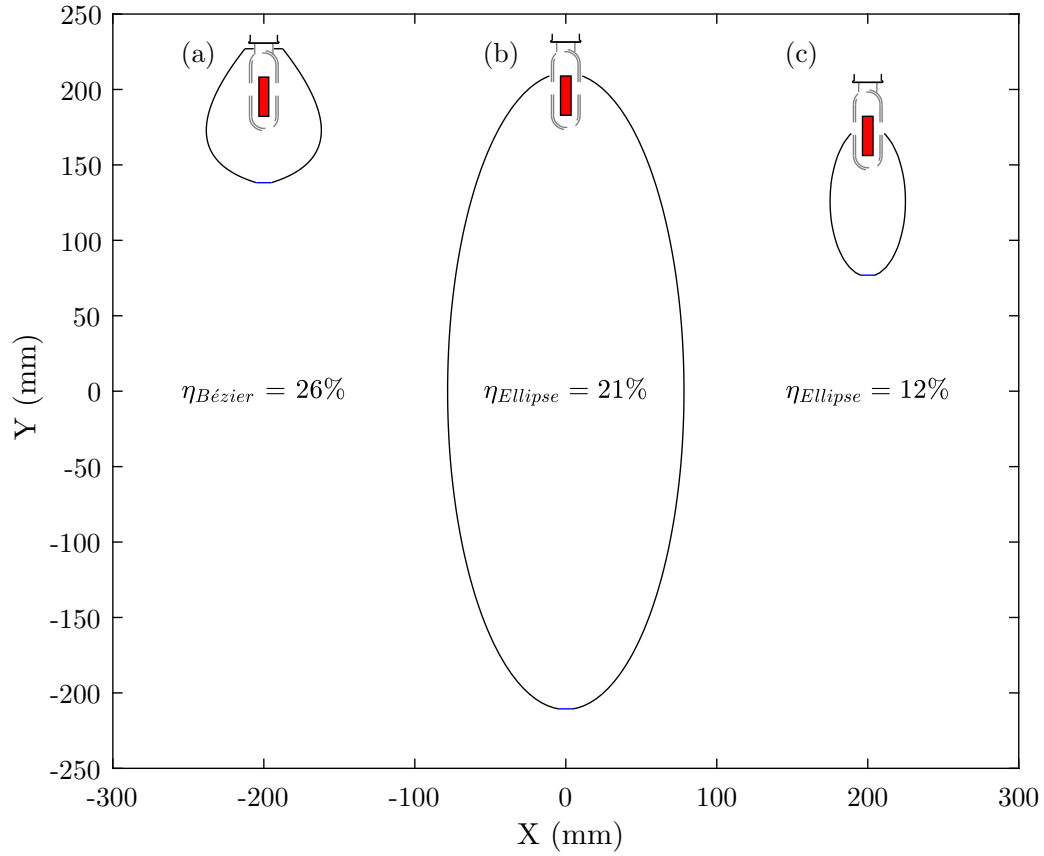


Figure 6.7: The efficiency of the optimised Bézier and elliptical reflectors for the 1000 W QTH lamp: (a) the optimised Bézier shape, (b) an optimised ellipse and (c) the most efficient 100 mm long ellipse tested.

6.5 Reflector design

The optimised 2D shape will be used to create an axisymmetric reflector by revolving the shape about its axis of rotation. This axisymmetric design will be manufactured and tested with Al and Au-coated reflectors. There are several considerations relevant to the operation and performance of the device which will be addressed in this section:

1. Manufacturing and finishing of the reflector.
2. The strategy for holding the lamp and insertion into the reflector enclosure.
3. The cooling system design.

6.5.1 Manufacturing and finishing procedure

The reflector was designed in such a way as to enable the polishing process, assembling and disassembling of the reflector, and replacement of the lamp without the need to dismantle the reflector. This was achieved by dividing the reflector longitudinally instead of laterally, as shown in Fig. 6.8. As a result, the reflector could be more readily polished than if manufactured in two halves along its width, as it provides access to the deep curvature of the shape. A highly concave freeform shape is difficult to access with a buffing wheel. Dowels ensured the correct alignment of the two reflector halves during assembly. A full set of engineering drawings and dimensional specifications of the reflector can be found in Appendix D.

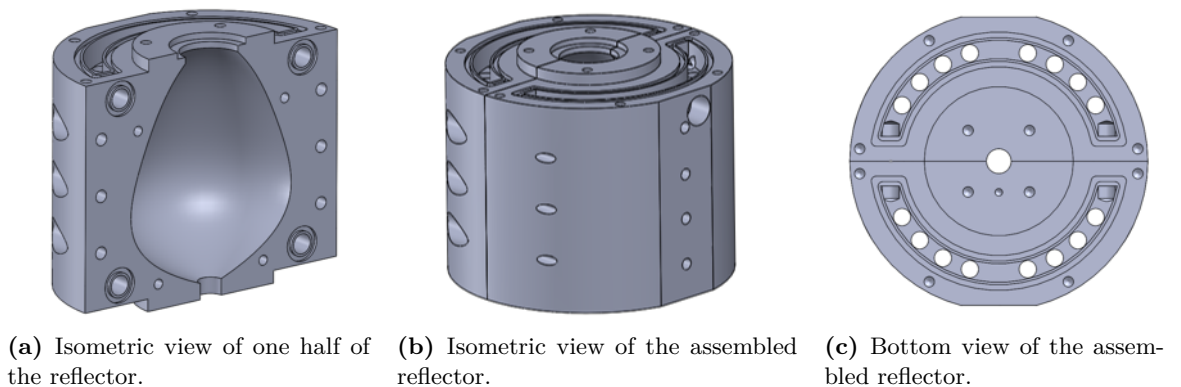


Figure 6.8: SolidWorks views of the reflector assembly.

The manufacturing procedure for the concave surface of the reflector is key to reducing finishing time and obtaining a highly reflective surface. After manufacture of the reflector halves, the internal surface was finish machined using a 3 mm radius ball nose milling cutter.

A rough cut was first performed before a final pass at 900 mm/s with a cut width of 0.035 mm while the cut depth was varied depending on the incline of the surface. A photograph of the finish produced by this process is provided in Fig. 6.9a.

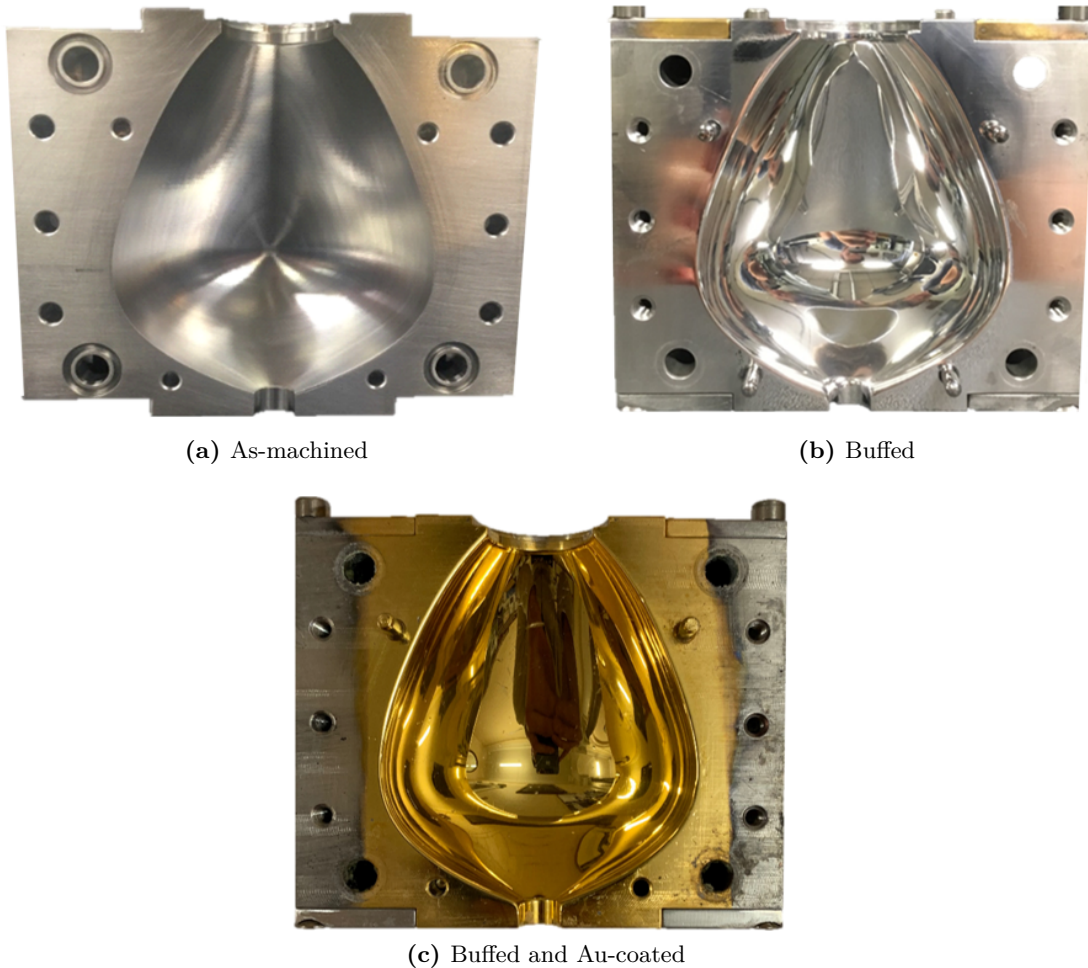


Figure 6.9: Photographs of the manufactured and finished Al and Au FIRHs.

Buffing wheels of various grades were employed to allow the surface to be finished to an appropriate smoothness for use as a specular IR reflector. This was performed using a rough polish with Menzerna 439T compound and a final polish using Menzerna P175 superfinish compound (Menzerna, Germany). The initial step required approximately 1 hour of buffing per reflector half, while the final step required approximately twice that time. Polishing was concluded when inspection indicated that there were no visible defects on the concave surface of the reflector. The resulting finish from this process is shown in Fig. 6.9b. The Au-coated reflector (Teer Coatings Ltd, UK) is also shown in Fig. 6.9c, which was prepared using the same procedure as the Al before the coating process was carried out. The coating

processes involved first applying an adhesion layer of Ti to the reflector surface, followed by a $1\text{ }\mu\text{m}$ coating of Au.

To characterise the surface finish of the reflector surface, a flat $30\text{ mm} \times 30\text{ mm}$ Al 6082 sample was prepared using the same polishing procedure described, although the process was considerably shorter given the smaller surface size. A comparative surface was also polished using standard metallographic procedures using P180 grit, P1200 grit, $6\text{ }\mu\text{m}$ diamond suspension, and $1\text{ }\mu\text{m}$ diamond suspension. The average surface roughness of the two samples was measured using white light interferometry (WLI) at a magnification of $10\times$ (Filmetrics, Profilm 3D). The data was first adjusted to level the surface and then outlier points with a slope of greater than 60 degrees were removed and filled, similar to previous work of the author [77]. A WLI map of both samples is shown in Fig. 6.10 with average values of as 25 nm and 18 nm for the buffed and polished sample respectively. Although the buffing procedure was a less well-controlled process, it delivered a surface finish which was only marginally rougher than the conventional process. It is noted, however, that the samples tested were small and flat and therefore easier to polish to a consistent finish than the large concave reflector surface. Hence, the characterisation presented is an ideal representation of the polishing process on the reflector surface. Unfortunately, it was not possible to characterise the roughness of the curved reflector surface directly with the equipment available at the time. However, this analysis shows that the approach employed is comparative to standard metallographic procedures, albeit marginally less effective. Contact was made with suppliers electropolishing and chemical polishing services in order to obtain a higher quality

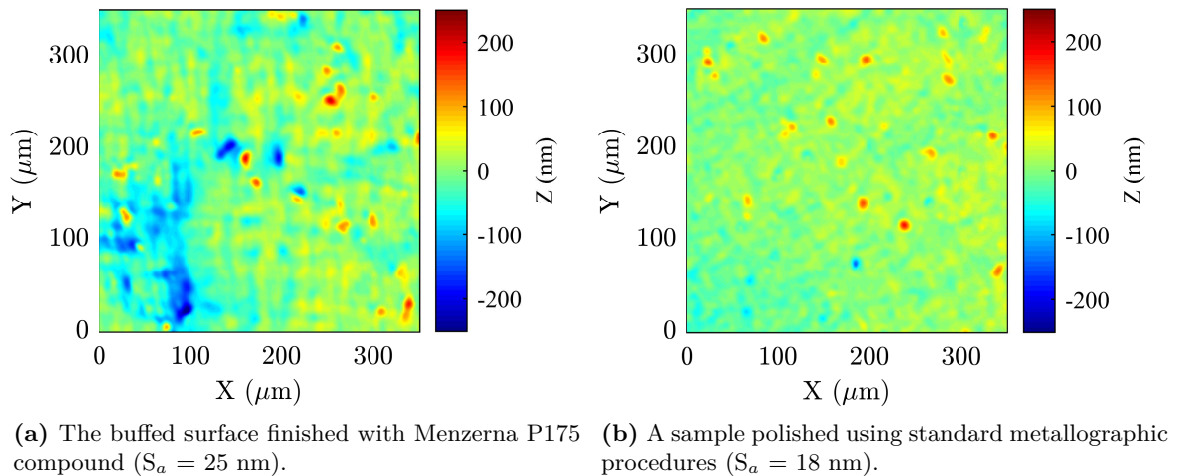


Figure 6.10: WLI maps of two finishing processes.

surface finish; however, there was a lack of interest shown by these suppliers due to the small number of components to be finished.

6.5.2 Lamp holder design

Since the reflector will be water-cooled, it is important that the design allows the holder to be replaced without the need for the entire reflector to be disassembled. Further, effort should be directed to maximise the reflective surface area to increase the reflector efficiency and reduce losses through the lamp inlet orifice. This can be achieved by tightly fitting the holder around the lamp base to reduce the radiation lost through the lamp insertion point. Fig. 6.11 shows (a) a side view of a holder half and (b) the two holder halves fitting around the 1000 W QTH lamp.

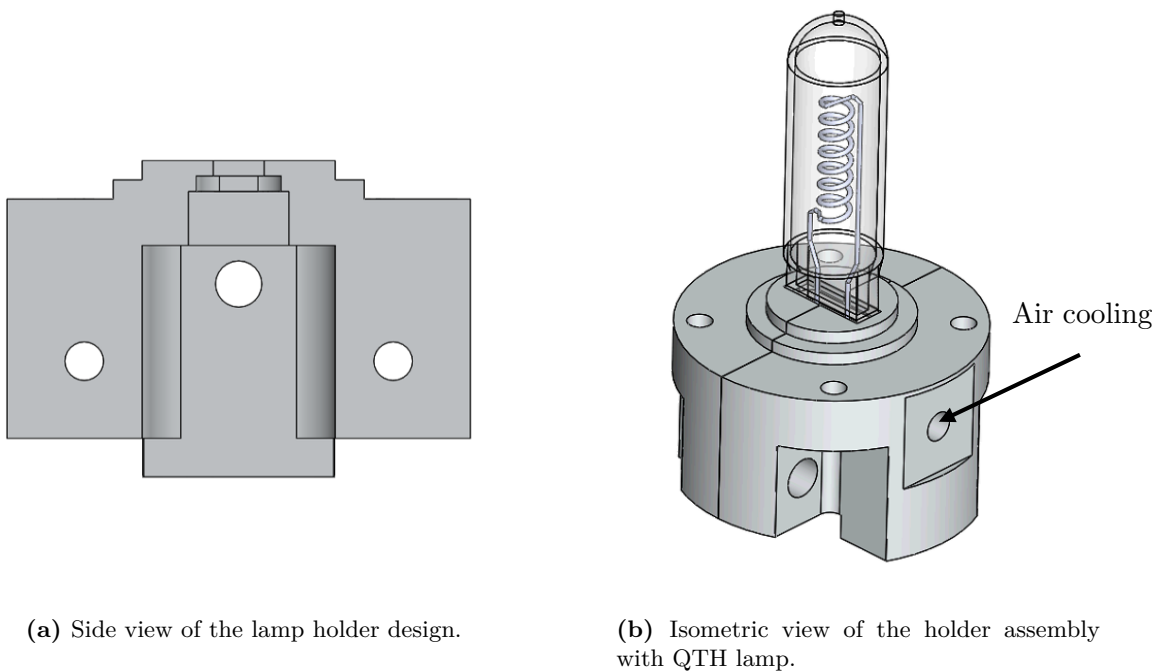


Figure 6.11: View of the lamp holder in SolidWorks.

The lamp base is a rectangular cross-section and measures approximately 19 mm by 6 mm although there is variation from lamp to lamp. An additional gap of 0.25 mm was added to each dimension to account for tolerances, which provided an outlet of 19.5 mm $\times$ 6.5 mm with a corresponding cross-sectional area of 126 mm². This is less than half the value of ~ 300 mm² required if the outlet was large enough for the quartz envelope to pass directly to the reflector enclosure. In addition to the water-cooling, a jet of compressed air was directed

at the base of the lamp to maintain a low temperature. Air entered through the cooling hole drilled into the side of the holder and then was directed towards the base of the lamp.

6.5.3 Cooling system design

The reflector was designed to be cooled by water to maintain a low reflector wall temperature during operation (i.e. $<50^{\circ}\text{C}$). The reflectivity of Al and Au decreases with a rise in temperature [164] and hence, ensuring that the temperature of the reflector wall is minimised will improve the performance of the device. The cooling channels were integrated into the reflector body by boring a series of channels that run parallel to the length of the reflector, as shown in Fig. 6.12. The coolant entered one half of the reflector and exited from the opposite corner of the second half, guaranteeing that the coolant flowed through the whole reflector in a somewhat homogenous flow pattern. A set of cover plates sealed with an o-ring were fastened on top of the channels, which allowed the cooling channels to be manufactured and the reflector sealed afterwards. The maximum temperature reached by the reflector during operation with this cooling design was found to be less than 40°C . Further details of this experimental data can be found in Appendix C.1.

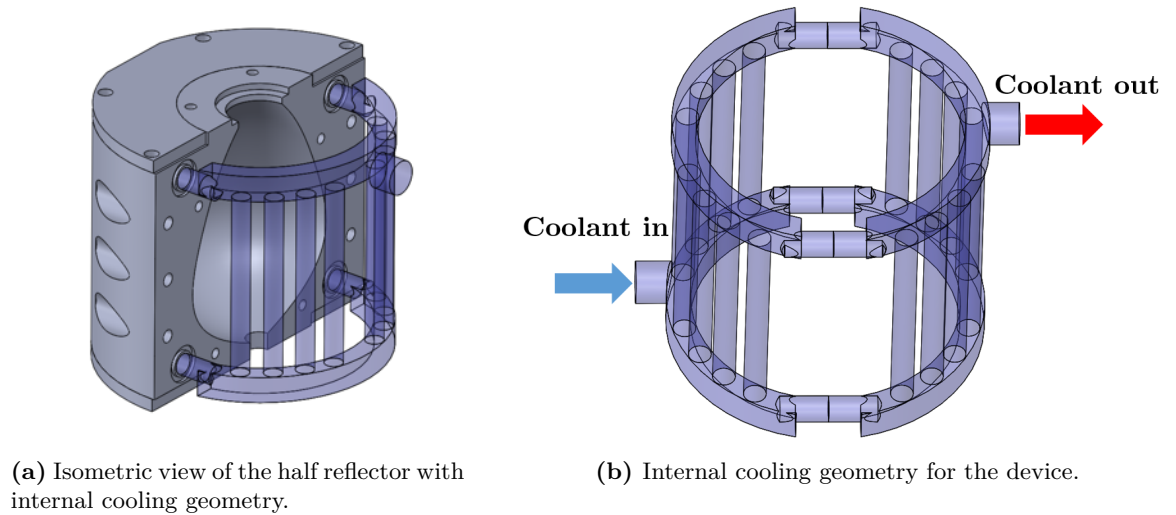


Figure 6.12: SolidWorks view of the coolant flow design.

6.6 Characterisation of the optimised FIRH

The GA optimised FIRH must be thoroughly characterised to understand the performance characteristics and limitations of the device. Characterisation of the device is achieved by determining the startup time of the device, measuring the power output and efficiency, measuring the filament temperature, characterising the shape of the reflector, and estimating the light recycling factors for the two reflector coating types.

6.6.1 Startup time

The startup time for IR sources is typically much lower than that of other heating strategies such as convection and conduction. The startup time for QTH lamps in unconfined conditions was investigated by Bedard [35] and Pettersson & Stenström [36]. The startup time was shown to be relatively quick, with the majority of the lamps' total radiation output reached within seconds of initial voltage application. For example, Bedard found that the QTH sources reached over 60% of the peak output in less than 2 seconds. It would be anticipated that the startup time of the enclosed FIRH may take longer since the mass of the reflector and cooling system will also need to reach equilibrium.

Fig. 6.13 shows the startup time of the Au-coated FIRH at 100 and 200 V compared to the QTH lamp in open air at 200 V. The QTH lamp in open air has the fastest startup time reaching 90% of its peak value within 3 seconds and 100% reached in just over 2 minutes. The Au-coated IR heater requires longer to reach equilibrium than the open lamp, with 90% of the peak value reached within ~50 seconds and 100% reached within ~3 minutes. The input voltage has an effect on the startup time with the test at 100 V taking ~50% longer for both the 90% startup time and the time to 100% radiative power output when compared to the 200 V case. It is concluded that similar to the QTH source, the FIRH can be used almost immediately after startup with minimal reduction in power, highlighting a distinct advantage over alternative heating methods.

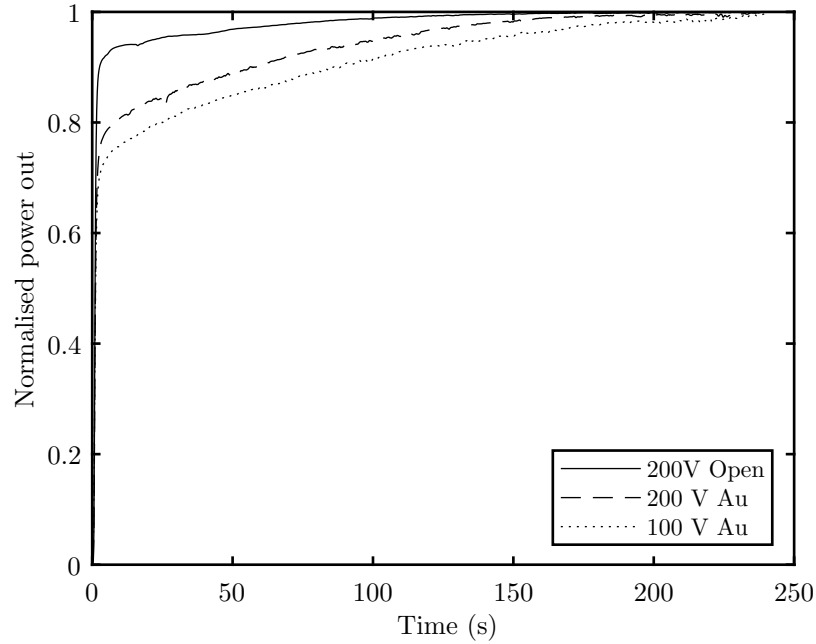
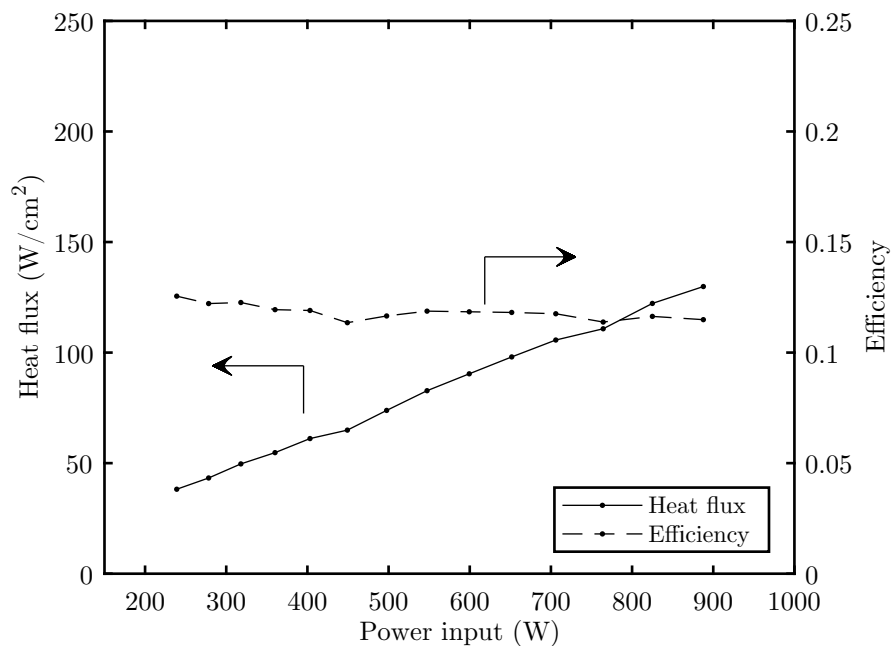


Figure 6.13: Startup time of the QTH lamp and Au reflector at 200 V input and 100 V input.

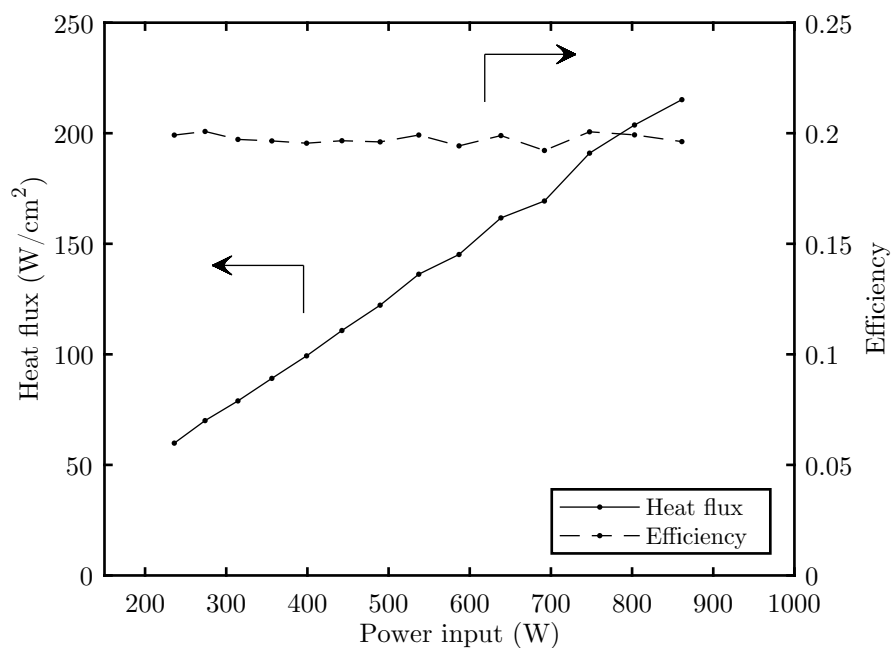
6.6.2 Power output and efficiency

The power output of the FIRH was measured using the FLASH-500-55-C measurement device, which in conjunction with the power input to the lamp, allows the reflector efficiency to be determined. The power output and efficiency of the Al FIRH are shown in Fig. 6.14 measured in steps of 10 V from 100 V to 230 V. The efficiency of the Al reflector marginally decreases across the range of power inputs tested, reducing from 12.5% to 11.5%. The heat flux increases monotonically with power input from the lowest measured value of 38 W/cm² to the maximum value of 130 W/cm². The Au-coated reflector delivers significantly higher heat flux and efficiency than the Al-coated unit across the entire test voltage range due to the higher reflectance of the material, as shown in Fig. 6.14. At the highest voltage tested, the Au reflector delivered 215 W/cm², which is over 60% greater in comparison to the Al reflector. This indicates that the additional cost associated with the Au coating is worthwhile for applications which require high heat flux.

The reflector efficiency remaining relatively constant across the entire voltage test range is an interesting result. One would expect that since the radiative efficiency increases with filament temperature, a higher filament temperature would lead to an increase in reflector performance. Besides the difference between η_{rad} of the lamp at 2400 K and 3000 K being only $\sim 5\%$, several other potential factors can explain this result. Firstly, as the temperature



(a) Power output and efficiency of the Al FIRH.



(b) Power output and efficiency of the Au FIRH.

Figure 6.14: Power output and efficiency of the Al and Au-coated FIRH from 100 to 230 V input.

of the filament is increased, a higher proportion of radiation will be emitted in the UV-vis range, which has a lower reflectivity than in the IR range for both Al and Au material types. Conversely, at lower temperatures, the wavelength distribution is longer on average, which is more likely to be absorbed by the quartz envelope. This was discussed when investigating

the radiative efficiency of the lamp in Chapter 3; however, in the case of the FIRH, the rays will potentially pass through the quartz envelope more than once and thus this will have a more considerable effect in this scenario. The overall trend of a relatively constant or marginally decreasing efficiency across the range of powers tested may be attributed to the cancelling of the increased quartz absorptivity, reduced radiative efficiency at lower filament temperatures and the decreased reflectivity of the walls at higher filament temperatures.

6.6.3 Filament temperature

Since a highly reflective enclosure surrounds the filament, the resistance associated with heat flowing from the filament to the surroundings through both radiation and convection will rise, and therefore cause an increase in the source temperature for a given power input. Unfortunately, this will mean that the life of the lamp will decrease [41]. This issue may be alleviated by limiting the maximum temperature of the filament to that of a filament operating under unconfined conditions. Therefore, it is necessary to study the temperature of the filament should be studied while operating under these conditions.

The temperature of the filament is plotted against the voltage input when operated in open-air, within the Al reflector, and within the Au reflector in Fig. 6.15. The temperature of the filament during operation in open-air conditions is significantly lower than when operated inside the highly reflective enclosures. The peak temperatures for the open, Al and Au-coated operating conditions at 230 V was found to be 2960 K, 3063 K and 3144 K respectively. The power input to the lamp should be adjusted to maintain the filament temperature at a similar level to that of the lamp in open-air (i.e. ~ 3000 K) to ensure the longevity of the lamp. This reduces the operation heat flux of the Al and Au reflector to 115 W/cm^2 and 170 W/cm^2 respectively. However, if higher heat fluxes are required for short periods, this limit can be exceeded but at the cost of the life span of the lamp.

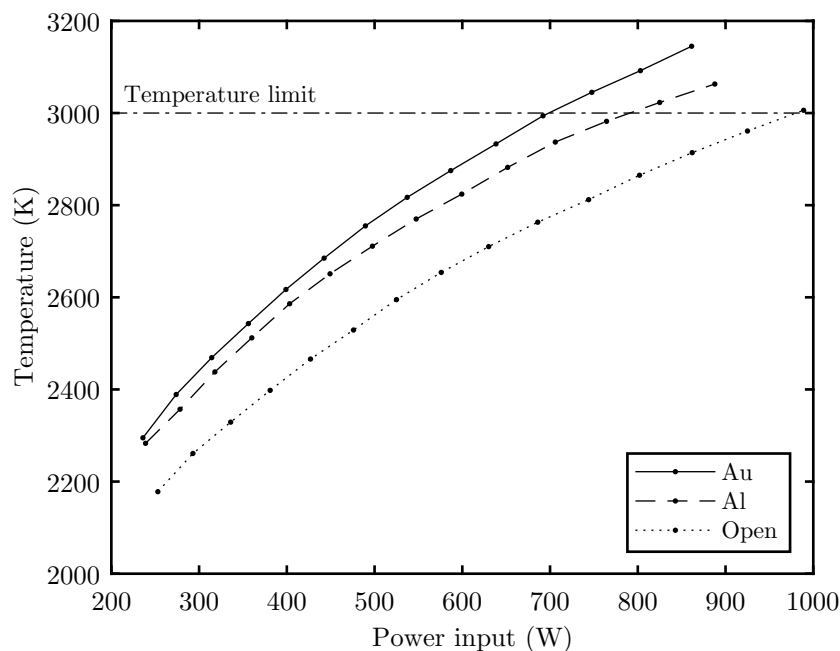
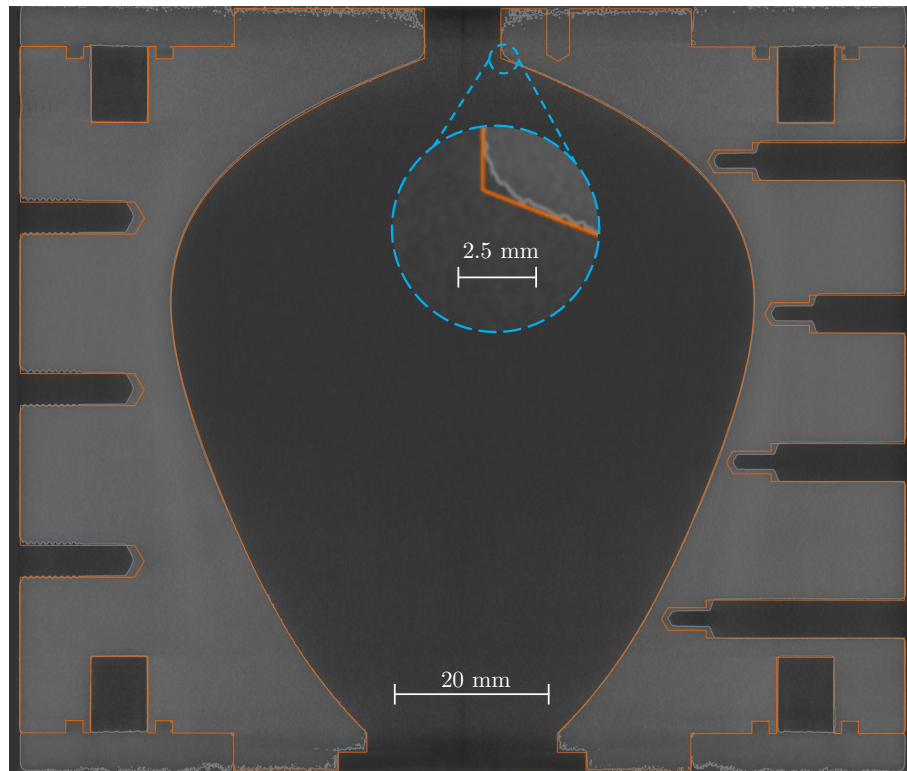


Figure 6.15: Filament temperature during operation for the Au reflector, the Al reflector, and the lamp in open-air conditions.

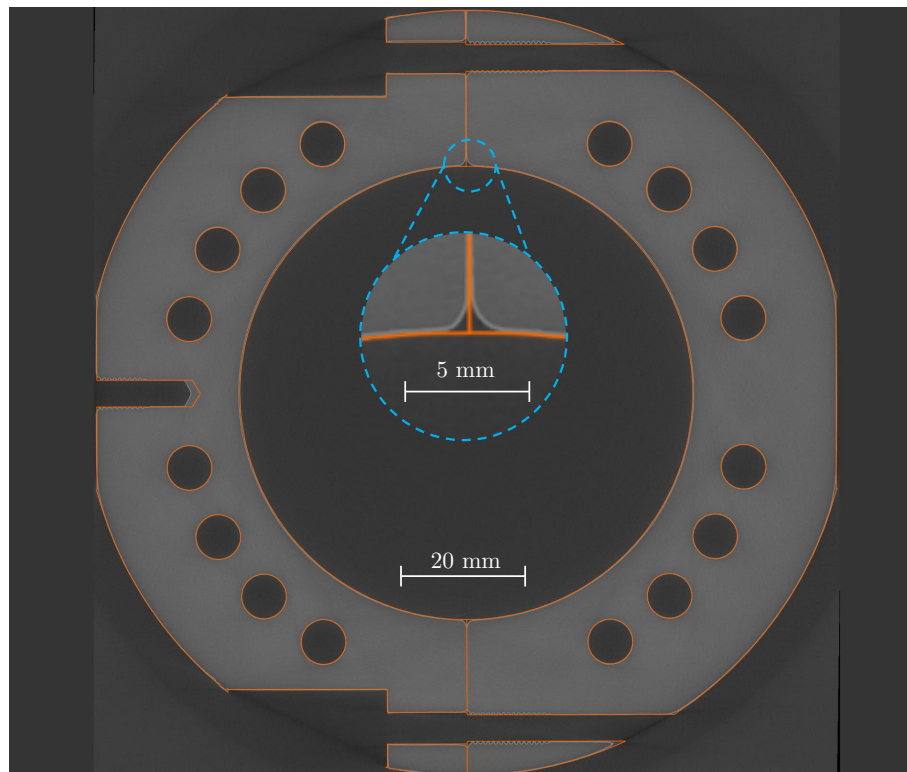
6.6.4 Reflector shape characterisation

A 3D model reconstruction of the reflector was carried out using x-ray computed tomography (XT H 320, Nikon) with a voxel size of $68 \mu\text{m}$. The scan process involves obtaining hundreds or even thousands of x-ray images of a sample from various angles, which allows the reconstruction of a 3D model and comparison to a nominal geometry. This allowed the shape of the reflector to be characterised and the identification of deviations of form from the ideal geometry due to the manufacturing and finishing process.

Fig. 6.16 shows a side and a top view of the reflector. Overall agreement is shown for the form of the reflector, with the profile of the CAD and CT scan aligning extremely well across the entire length of the reflector surface. The difference between the CAD and manufactured geometry is clear near the tapped holes and thermocouple holes on the left and right-hand side of Fig. 6.16. There are a number of minor discrepancies in the actual reflector geometry due to the buffing process employed. As shown in the zoomed inset of Fig. 6.16a, rounding of the edges occur at the exit of the reflector. Furthermore, the two edges at the join of the reflectors experience a similar deviation, as shown in the inset of Fig. 6.16b.



(a) Side section view of the reflector.



(b) Top section view of the reflector.

Figure 6.16: Comparison of a CT scan of the FIRH to the nominal CAD geometry. The CAD outline is shown in orange while the reflector bulk is shown in a light grey.

The radius of curvature along the join was measured to be ~ 0.6 mm. The total area this deviation affects can be estimated based on the product total of the edge length of the joint for each reflector half (224 mm) and the width of the strip (0.6 mm). Dividing this number by the reflector area, the affected area can be estimated to be $\sim 1.5\%$ of the total reflective area. This is a non-negligible deviation which will adversely affect the performance of the FIRH. Steps to address this will be detailed in the following sections. Aside from these deviations, the difference between the manufactured reflector and nominal CAD geometry is minor, and it can be concluded that the manufacturing and finishing process employed allowed a shape which closely matches the specified CAD geometry to be fabricated.

6.6.5 The rate of light recycling

Due to the lamp being enclosed by the reflector, the rate of light recycling will also increase. This can be estimated based on the power output reduction of the lamp when operated under various conditions at a constant temperature. First, the “convex” radiative power output of the lamp can be estimated. The convex power output is the power that would theoretically be dissipated by the lamp in the case that the surface was convex and no light recycling occurs. The convex power output can be estimated using the Stefan-Boltzman law for a temperature of 3000 K, the spectrally averaged value for tungsten, and the area of the filament determined in Chapter 3:

$$P_C = \varepsilon \cdot \sigma \cdot A \cdot T_s^4 = 1415 \text{ W} \quad (6.1)$$

This is compared to the interpolated value of 930 W dissipated at 3000 K from the lamp in open-air conditions through radiation. The power factor, which is referred to as γ in this work, is a parameter which describes by how much the power output from the filament is reduced due to the effects of light recycling and is a function of the emissivity and recycling factor [47]. This allows the light recycling rate to be found for this lamp:

$$\gamma = \frac{(1 - \xi)}{1 - \xi(1 - \varepsilon)} = \frac{930}{1415} \quad (6.2)$$

This results in a spectrally averaged “base” recycling factor ξ_B of 0.61 for this lamp. This aligns with the work of Fu who found that the recycling factor for the single-coil configuration was ~ 0.3 - 0.4 depending on the location of emission on the filament. A significantly higher

recycling factor would be anticipated for the double coiled filament.

The lamp within the Al and Au reflectors dissipate 791 W and 698 W of radiative power at 3000 K, respectively, which results in recycling factors of 0.73 and 0.77. Based on these values, Fig. 6.17 shows the power dissipated and the corresponding effective heat flux output for each of the operating conditions. As the level of confinement is raised, the power output reduces and the effective heat flux enhanced. At the highest levels of confinement, the effective heat flux output of the QTH lamp is estimated as $\sim 315 \text{ W/cm}^2$, which is double that of convex tungsten. Exchanging power output for effective heat flux is advantageous as this allows a higher power density to be achieved, and the quality of the emission from the source to be enhanced. The results of this analysis are summarised in Table 6.2

Table 6.2: Light recycling characterisation of the 1000 W lamp.

Condition	Radiative power P_{rad} (W)	Recycling factor ξ	Power factor γ	Effective emissivity ε
Convex	1415	0	1	0.33
Base	931	0.61	0.66	0.56
Al reflector	751	0.73	0.53	0.64
Au reflector	663	0.77	0.47	0.69

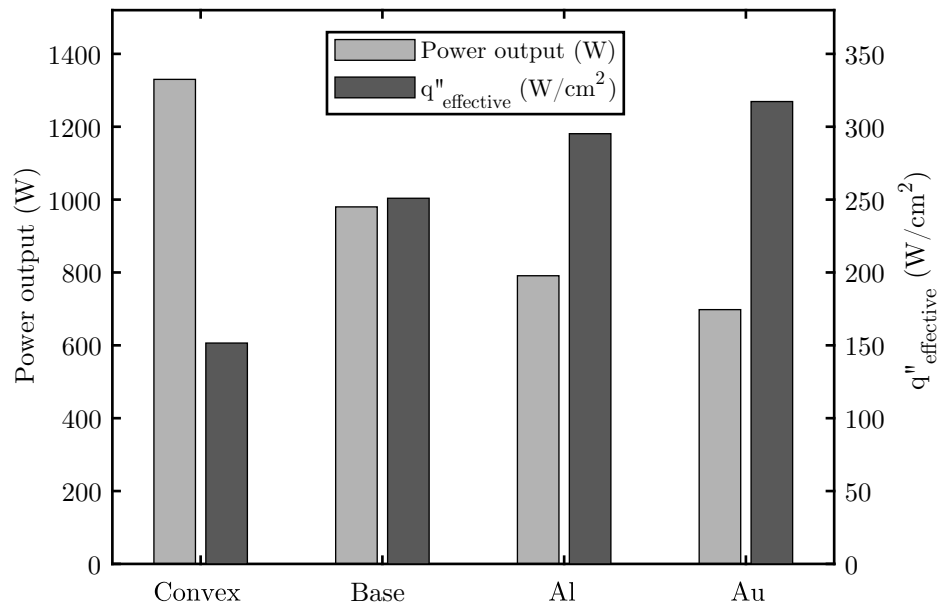


Figure 6.17: Comparison between the power dissipated and effective emissivity for the 1000 W QTH lamp based on light recycling factors.

6.6.6 Comparison to theoretical maximum and commercial devices

Fig. 6.18 shows the heat flux output of the various IR heaters compared to theoretical limits at 3000 K. The theoretical maximum for a blackbody and for a FIRH (derived from the light recycling factors) are shown at 460 W/cm² and 315 W/cm² respectively. The optimised design delivers considerable improvements over the commercially available units.

In comparison to the SpotIR heater, the Al reflector delivers nearly 30% higher efficiency as shown in Table 6.3. The heat flux output is even higher, with an almost 3× improvement. The optimised Au FIRH also demonstrates superior performance with a doubling of the efficiency and a 4× improvement in heat flux output.

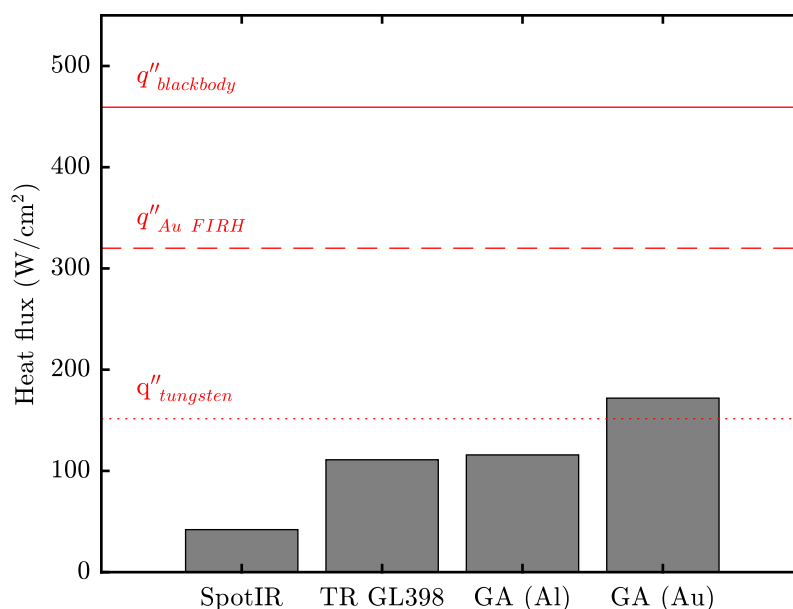


Figure 6.18: Theoretical maximums for the FIRHs considered in this work. The theoretical limit for convex tungsten, the optimised Au FIRH, and a blackbody at 3000 K are also included.

The Thermo Riko unit suffers from many of the same issues previously outlined with ellipses, and as a result, the Au optimised device outperforms in terms of efficiency despite the much smaller outlet size. The heat flux output of the optimised FIRH is much greater in comparison, although this is aided by the smaller outlet, which promotes light recycling. The Au optimised device also outperforms the theoretical maximum for a convex tungsten source due to the benefits of light recycling. Although this is a significant result in terms of progress over previous FIRHs, there is still potential for improvement in both the design process and overall performance of the FIRH.

A summary of the performance of the FIRHs developed and those available on the market that are of interest to this study is presented in Table 6.3. These devices deliver this improved performance at a reflector length which is less than half of that of the SpotIR heater. Similarly, the length of the optimised reflector is significantly smaller than the GL398 FIRH device, which may potentially open up use cases that were not suitable for IR technology previous to this work. These comparisons demonstrate the effectiveness of the optimisation process developed in this work.

It is very challenging to directly compare the various FIRHs since each has different outlet sizes, source sizes, and ratios between these features. This will be addressed later in this work in two ways. Firstly, reflectors for each of the sources used by the commercial FIRHs will be optimised using the same outlet area (see section 8.3 on page 204). This will allow a direct comparison between the optimised and commercial device without any discrepancy in the source size or the outlet size. Secondly, an approach for comparing the performance of reflectors with different source and outlet sizes will be developed based on a nondimensionalised analysis to follow (see section 8.5 on page 223).

Table 6.3: FIRH performance results adjusted to max operating temperature (*approximate value).

Manufacturer	Device	P_{in} (W)	P_{out} (W)	q'' (W/cm ²)	η	Length (mm)
PCS	SpotIR 4085	727	65	42	8.9%	200
Thermo Riko	GL 398	3000	350	111	12.0%	300*
-	GA (Al)	791	91	115	11.4%	90
-	GA (Au)	698	135	170	20.2%	90

6.6.7 Comparison to the 2D model

The model predictions for the Al reflector and the Au-coated reflector and the experimental measurements are shown in Fig. 6.19. For the Al reflector, the model predicts 15.8% efficiency versus the experimentally measured 11.8%, which is an overprediction of 33%. As for the Au coating, the model predicted 25.8% efficiency and 19.6% was experimentally measured. This is also an overprediction of 31%. In both cases, the error may be due to several factors such as the assumptions made in the model development, the experimental error associated with the power measurement, or measurement error associated with the material property inputs.

An apportionment for these errors will be described in detail for the 3D model developed later in this work in section 7.5.2 on page 186.

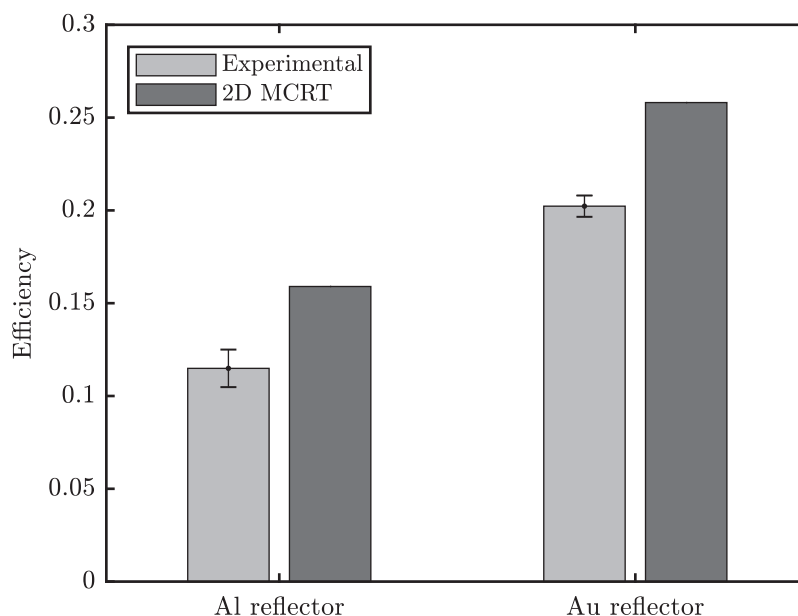


Figure 6.19: Comparison of the experimental power measurements and MCRT model.

The assumptions that are likely to be at fault are as follows:

1. The 2D model was used to simulate what is inherently a 3D radiation exchange process with the assumption that an optimised 2D shape would also be high performing in 3D.
2. The filament supports are neglected in this model, which if included, will undoubtedly decrease the efficiency prediction.
3. Lamp and reflector manufacturing differences that cannot be taken into account in the model.
4. Differences between the flat samples tested for reflectivity and the curved reflector surface may also explain the differences.

Several of these assumptions will be addressed in the model described in Chapter 7, allowing a more accurate representation of the radiation exchange within the reflector and higher-performing shapes to be obtained.

Despite these assumptions, the model and optimisation process successfully developed a custom shape which delivers improved performance over the commercial devices. Therefore,

the 2D modelling strategy can be adopted where there is a need to reduce computation time or model complexity while accepting there will be an inherent loss of accuracy.

6.7 Design process improvements

The assumptions made during the optimisation process should be addressed where possible to allow the development of a more representative model. Firstly, a 3D version of the model should be developed to more accurately model of what is inherently a 3D radiation exchange process. Further, the lamp supports should be incorporated into the model, as these will play a significant role in diffusing the radiation output from the source.

The optimisation process can be improved in several ways. Firstly, a higher-order Bézier curve can be used to allow a greater degree of freedom in the shapes that can be defined during the optimisation process. This will result in greater complexity and difficulty converging on a single shape. A larger population size may be required to compensate. For the prototype FIRH, the default parameters were used for the optimisation process and as discussed, the parameters of the GA can have a significant effect on the efficacy of the metaheuristic search; therefore, optimised parameters should be investigated which are suitable for the domain type under consideration.

For the manufacture and finishing of the reflector, effort needs to be focused on preserving the edges of the reflector surface. During the buffing of the reflector, the edges of the reflector bevel, which results in a deviation from the geometry specified by the optimisation process. Reducing this effect could be achieved by placing a cover plate over the edges being polished, or by carrying out further machining after the finishing process to create a new sharp edge. Improvements to the polishing process by applying a more controlled finishing procedure (i.e. electropolishing) would also undoubtedly improve the performance of the FIRH.

6.8 Conclusion

This chapter describes the design, optimisation, and characterisation of a custom FIRH. The research in this chapter demonstrates the ability of the optimisation methodology developed to design FIRH reflector shapes designed specifically for the size and shape of the IR source. Despite the assumptions applied during the modelling process, the optimised devices demonstrate appreciable improvement over the elliptical designs used by commercially available FIRHs. This indicates that the modelling and optimisation strategy of employing a 2D model has merit, and may be adopted in cases where model complexity and computation time are of particular concern.

The custom reflector shaped developed in this work delivered substantial benefits that can be classified into two categories:

1. The device delivers improved radiative performance in terms of efficiency and heat flux output.
2. The device is smaller in form than commercially available devices on the market and is a quarter of the length of the optimised ellipse shape found using the 2D model.

These advantages imply that focused IR technology may now be suitable for a wider range of applications where space or heat flux requirements may have previously limited their use. This attests to the viability of using this design methodology for the optomechanical design of FIRHs and other related fields.

Chapter 7

3D MCRT model development

7.1 Introduction

This chapter will follow on from the 2D model development to establish a more comprehensive 3D model, which can accurately predict the radiative performance of a FIRH. Many of the same procedures are reused from the 2D model and therefore are not detailed, except where there are significant differences between the respective implementations. Notably, the seeding process for the rays on the 3D filament and the algorithm employed for testing the intersection with the reflector changed considerably. Two algorithms were developed specifically for this work to improve the speed and accuracy of the intersection tests when compared to the methods described in the literature.

The 3D MCRT algorithm is validated to ensure that the predictions align with other RT packages and experimental measurements. The GA input parameters are also optimised to find the most suitable settings for this solution domain using the Taguchi experimental design method. Finally, the run time of the MCRT model is optimised by balancing the number of rays with the statistical error inherent to the MC method.

7.2 3D MCRT model

7.2.1 Simulation domain

The simulation domain for the 3D model is shown in Fig.7.1 using a sectioned view of the reflector to illustrate each component. The optimised reflector shape that was found in Chapter 6 is presented in this example. The supports are shown in black, while the quartz envelope is a transparent grey. The filament is constructed using a series of tori with the centre of the filament “body” located 33.5 mm from the top surface of the reflector. The assumption of using tori to represent the filament is similar to the one applied in the axisymmetric numerical model developed in Chapter 3. The top surface of the reflector has a $6.5 \text{ mm} \times 19.5 \text{ mm}$ orifice to allow the lamp to be inserted inside the reflector.

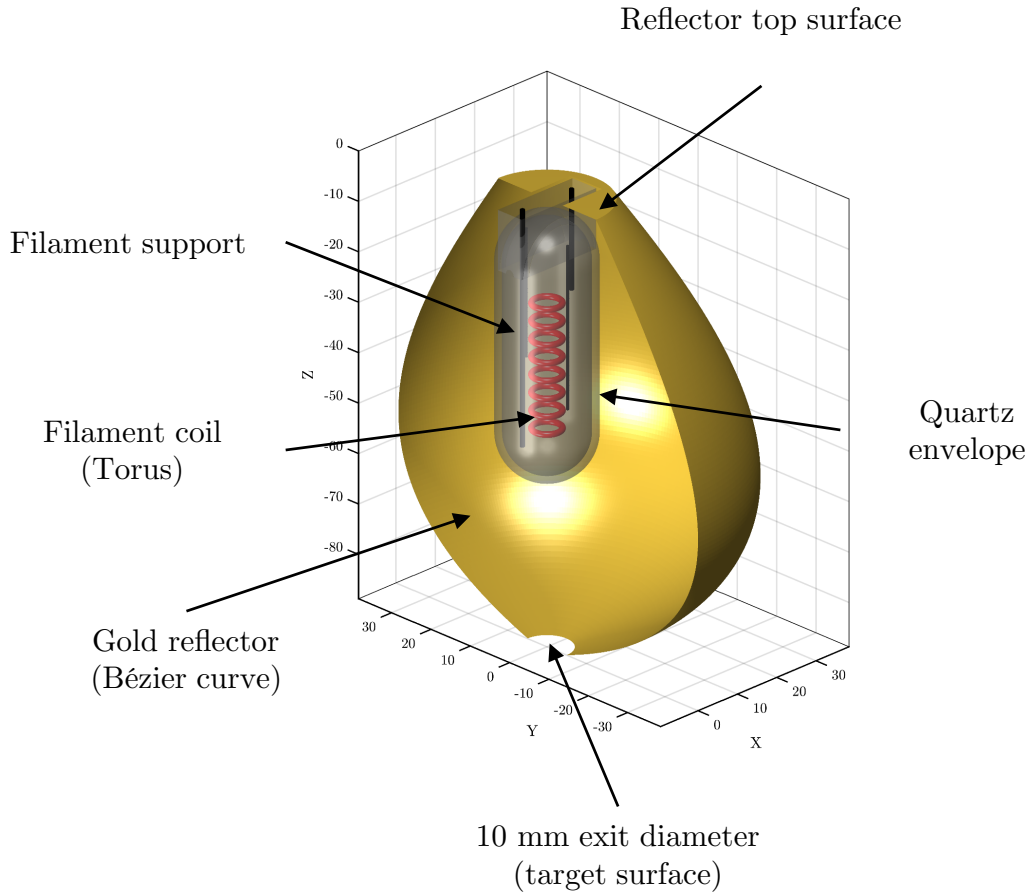


Figure 7.1: Simulation domain for the 3D model with the 1000 W lamp.

The assumptions made during the 2D modelling process will again be employed with the exception of the following:

- The rays will now be traced in 3D, which allows the path of the rays and the distribution

within the reflector to be more accurately represented.

- The filament supports are included in the model as solid molybdenum bodies.
- The filament is represented as a torus shape, which more closely represents the geometry of the coiled structure.

7.2.2 Ray tracing procedure

The procedure for ray tracing a FIRH with the 3D MCRT model is the same as described for the 2D model in section 5.5.2 and will be expanded upon in the ensuing sections.

7.2.3 Initialisation

The first step to initiating the ray tracing algorithm is the seeding of ray positions and ray directions. Since the equations which describe the seed positions and vector directions change from a 2D to a 3D implementation, the details will be described. The properties of each ray (wavelength, absorption index, refractive index, reflectivity with surfaces at that wavelength) will be defined using similar methods to that described in section 5.5.3 and therefore will not be expanded upon further.

7.2.3.1 Ray seeding

A filament composed of a single-coil can be mathematically described by the equation of a helix. A double-coil requires the inclusion of another helix which is superimposed onto the first, resulting in the complex coiled-coil geometry. However, testing for the intersection on a helix, which may have 10's or even 100's of intersections along a given ray path, is not feasible to implement into the MCRT model for use with a GA optimisation process. The most accurate representation of the filament for which an intersection can be tested in a time efficient manner is a series of tori. Therefore, eight tori with a minor radius the same as that of the small coil of the filament, and a major radius set as that of the large coil of the filament is employed. The selection of a seed point on the series of tori can be determined using a predefined integer and three random numbers:

1. An integer between one and the number of tori is used to select the torus from which the ray will be seeded. This is preselected deterministically to ensure that there is an equal number of rays distributed on each torus. This is a stratified sampling technique

[22] which reduces the variance of the process by preventing the rays from grouping on a single torus.

2. A random number, referred to as $\theta \in [0, 2\pi]$, is used to determine the angle of the seed point on the minor radius (r).
3. A second random number, $\varphi \in [0, 2\pi]$, is used to determine the angle of the seed point on the major radius (R).

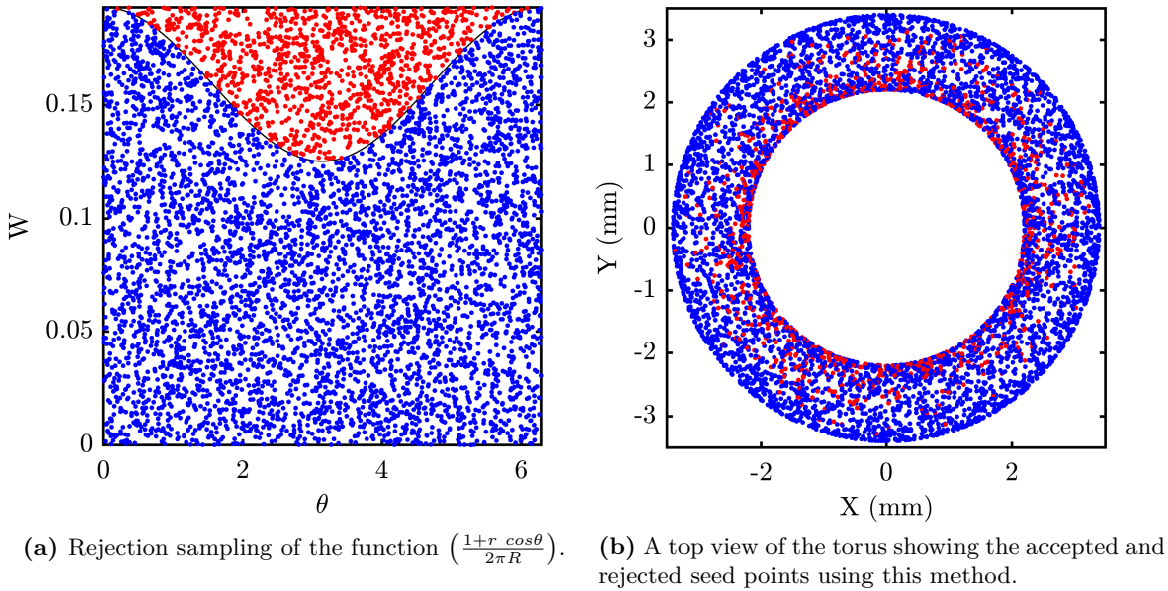


Figure 7.2: Random seeding on a torus. The accepted seed points are shown in blue while the rejected seed points are in red.

These random variables can be converted into Cartesian coordinates using the following equation:

$$f(\theta, \varphi) = [(R + r\cos(\theta))\cos(\varphi), (R + r\cos(\theta))\sin(\varphi), r\sin(\theta) + Z_{torus}] = [x, y, z] \quad (7.1)$$

where Z_{torus} is the height of the selected torus. This method will seed the rays with a higher density on the inside of the torus due to the reduced surface area at this location, and therefore, a proportion of the generated rays must be rejected to ensure even distribution of the seed points. A third random number, W , is required for the following inequality [165].

$$W \leq \left(\frac{1 + r \cos\theta}{2\pi R}\right) \quad (7.2)$$

W is sampled between zero and the maximum value of the right-hand side of Eq. 7.2, which occurs when θ is zero or one ($W \in [0, \left(\frac{1+r}{2\pi R}\right)]$). If W is less than or equal to the right-hand side of the equation, the ray can be accepted; otherwise, the seed point is rejected. Fig. 7.2a illustrates the distribution function as θ is increased from 0 to 2π . A larger number of points should be seeded where θ is near 0 or 2π as this is the outside of the torus where the radius is larger. Conversely, the distribution reaches a minimum at π which corresponds to the inside of the torus. Fig. 7.2b shows a plan view of the distribution of seed points generated using this method around a torus. As shown, the rejected seed points tend to be located near the inside surface of the torus. The points are not uniformly distributed due to the random nature of the seed point selection process; however, the stratified method improves the distribution when compared to a completely random seed strategy.

The normal vector at a given point on the torus is required for either when seeding a ray or when a ray reflects on the surface. The θ and ϕ angles formed by the intersection on the torus can be substituted into the following equation to return the normal vector [166]:

$$\vec{N} = [\sin(\theta)\cos(\phi), \cos(\theta)\cos(\phi), \sin(\phi)] \quad (7.3)$$

7.2.3.2 Vector direction

The direction of ray emission is determined using a Lambertian cosine distribution, which can be derived using the following equation [22]:

$$(\theta, \varphi) = (\arccos(1 - R_1)^{\frac{1}{\gamma+1}}, 2\pi R_2) \quad (7.4)$$

This function transforms two uniformly distributed random numbers, $R_1 \in [0,1]$ and $R_2 \in [0,1]$ into the polar angles of θ and φ . In the equation, γ is the Phong exponent which when set to 1, produces the required cosine distribution with a Cartesian form as follows:

$$f(R_1, R_2) = [\sqrt{1 - R_1}\cos(2\pi R_2), \sqrt{1 - R_1}\sin(2\pi R_2), \sqrt{R_1}] = [x, y, z] \quad (7.5)$$

After the generation of the vector directions, each vector is rotated in 3D space from its starting position to final position using a rotation matrix. The rotation matrix is calculated as the rotation from $[0 \ 0 \ 1]$ to the normal vector at the seed location. A comparison between a cosine distribution and the generated distribution is shown in Fig. 7.3a and a distribution

of 1000 vectors is shown in Fig. 7.3b.

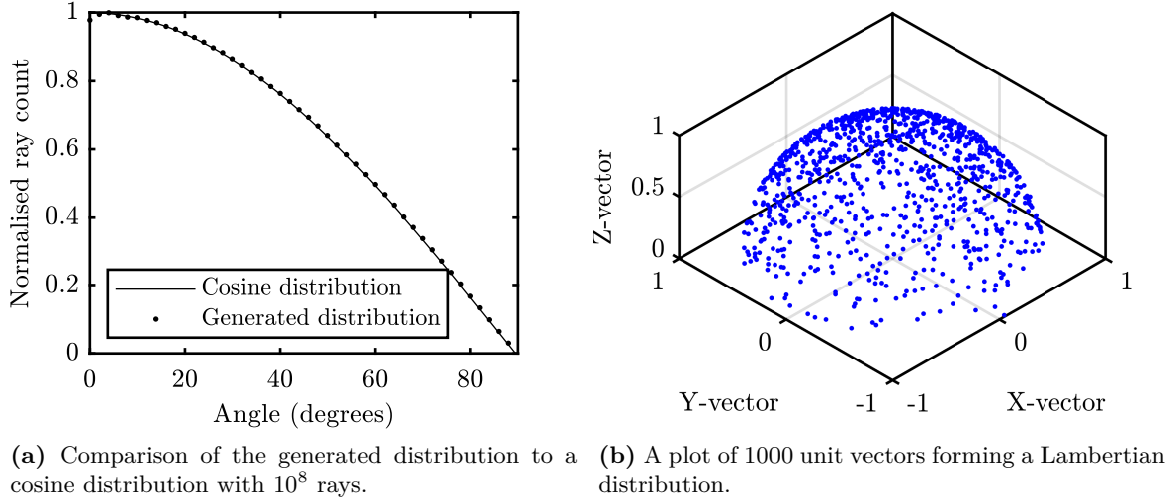


Figure 7.3: Generated Lambertian distribution.

7.2.4 Tracing inside the lamp

After emission from the filament surface, the ray may intersect several bodies, including the interior interface of the quartz, the filament supports, or the filament surface again. This process is illustrated in Fig. 7.4 and outlined in the following subsections.

7.2.4.1 Tungsten filament

The tungsten filament used in this lamp is a coiled-coil which is treated as a series of tori in the 3D model, as shown in Fig. 7.5a. The filament surface is again considered an emitter-reflector for the reasons described in Section 5.5.4.2 on page 117.

The tori filaments are enclosed by a cylinder of height 26 mm and radius 3.5 mm, which is used to test intersection with the filament in a more computationally efficient manner. This is referred to as applying a “bounding box” where complex structures can be obscured behind simpler ones that are more efficient to trace [167]. If intersection occurs with the cylinder, further tests are carried out to determine if the ray interacts with the enclosed tori. An intersection test can be carried out on the cylinder in 2D in the XY-plane using the equation of a circle with the same radius and origin as the cylinder. If an intersection point is found, the z-coordinate can be calculated using the vectorised equation of a ray (Eq. 5.4), and if this is within the upper and lower limits of the cylindrical body, the ray is identified as passing

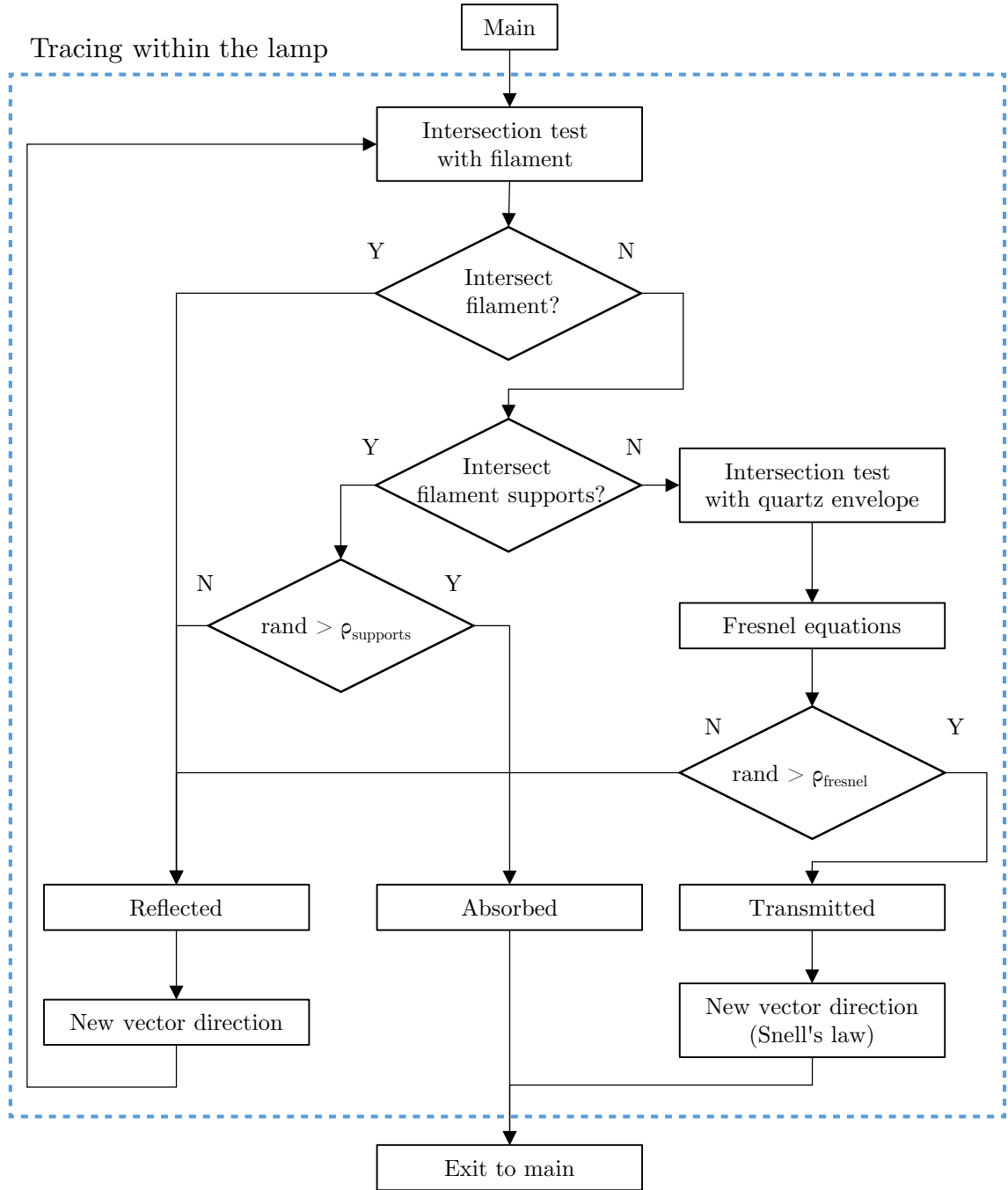
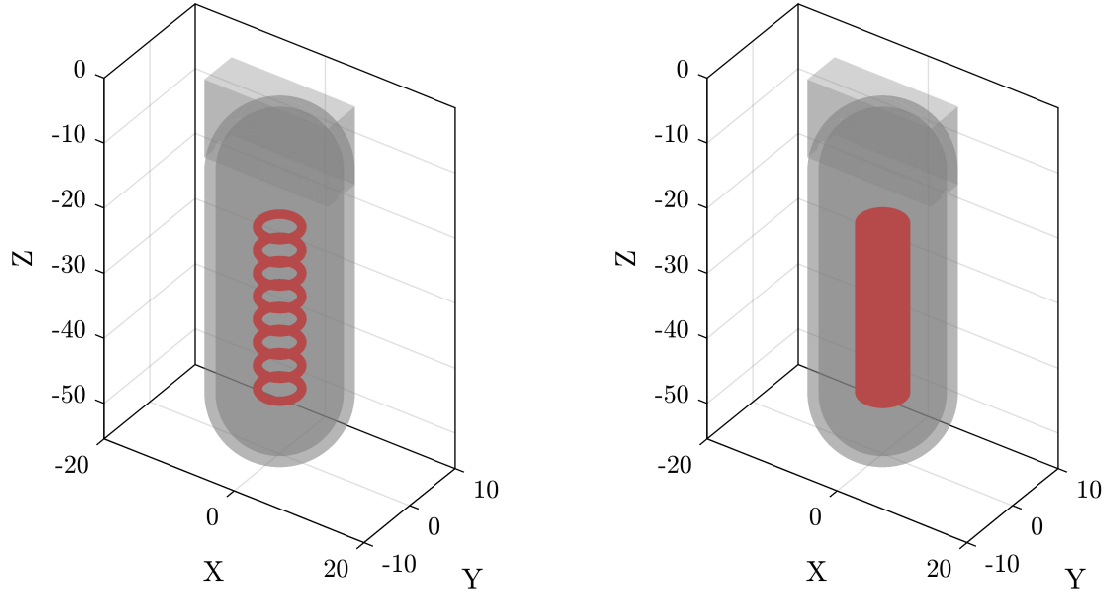


Figure 7.4: Flowchart of the 3D MCRT subroutine for a ray propagating inside the quartz envelope. This is an updated version of Fig. 5.12 on page 114.

through the cylindrical boundary. Each interaction with the cylinder will always have two intersection points unless the ray is tangent to the cylinder. The uppermost and lowermost value of the intersection points can be used to disregard particular tori from the follow on intersection tests, reducing computational time. The process of testing the intersection with the bounding cylinder and the series of tori is illustrated in Fig. 7.6a-c.



(a) A series of tori representing the filament surface.

(b) An enclosing test cylinder.

Figure 7.5: Implementation of the filament in the 3D MCRT model.

Testing intersection with the relevant tori begins with the Cartesian form of the equation of a torus:

$$(x^2 + y^2 + z^2 + R^2 - r^2)^2 = 4R^2(x^2 + y^2) \quad (7.6)$$

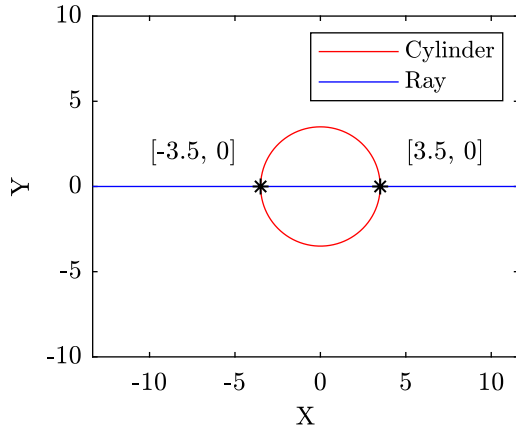
where R is the major radius and r is the minor radius. The variables x, y, z can be substituted for the single parametric variable t_r and known values:

$$x = P_x + t_R \times \vec{v}_x; y = P_y + t_R \times \vec{v}_y; z = P_z + t_R \times \vec{v}_z \quad (7.7)$$

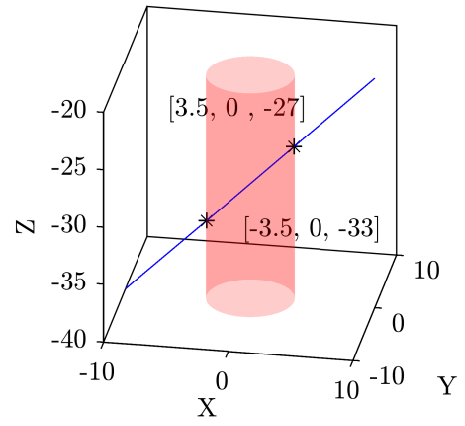
This substitution yields a quartic equation in the form of:

$$C_5 t_R^4 + C_4 t_R^3 + C_3 t_R^2 + C_2 t_R + C_1 = 0 \quad (7.8)$$

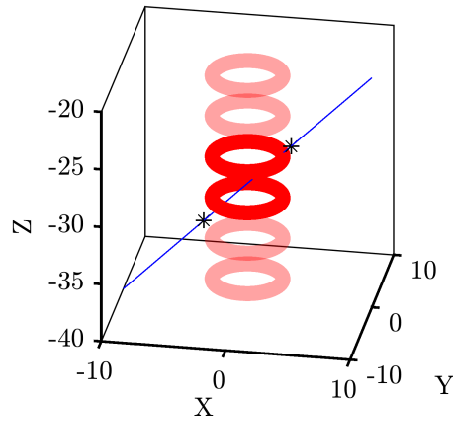
Computing the roots of a quartic equation is computationally expensive using numerical solvers. Therefore, as many tori as possible must be eliminated using the cylinder interrogation method. A ray can intersect a torus at up to four locations, as shown in Fig. 7.7. If no intercept is found, the roots of the equation will be returned as complex numbers which can then be disregarded. Finally, in the case that the ray is tangent to the torus, only a single root will be returned.



(a) 2D intersection with a circle in the XY-plane.



(b) Determine the z-coordinates of the intersection in 3D.



(c) Intersection test with relevant tori (deep red) after discarding tori which the ray cannot interact with (light red).

Figure 7.6: Intersection tests with an encapsulating cylinder and tori.

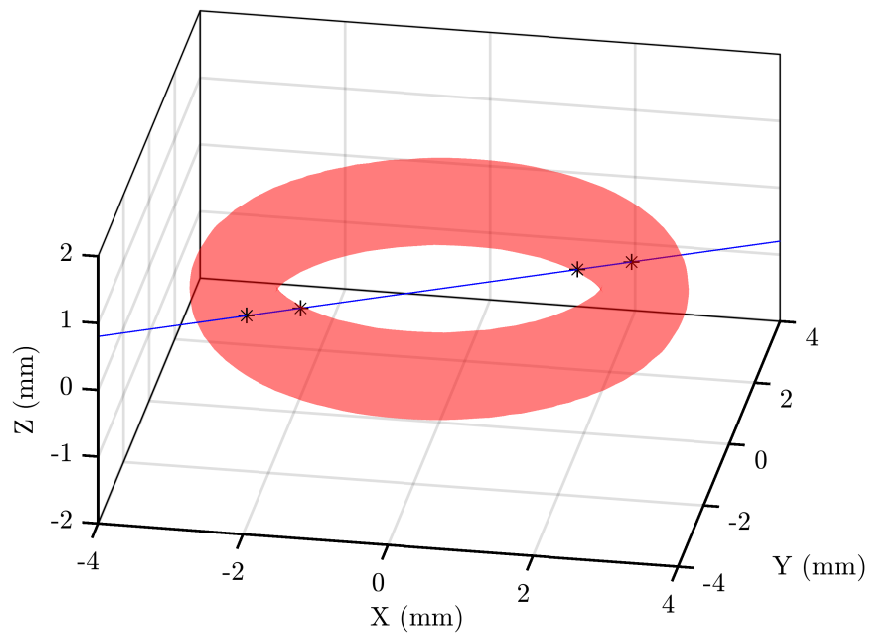


Figure 7.7: Ray intersection with a torus showing four intersection points.

7.2.4.2 Interior surface of the quartz envelope

The interior surface of the quartz envelope is modelled as a cylinder with hemispherical endcaps similar to the process described with the 2D model but extended to 3D shapes. The quartz base of the lamp is also included in the simulation as planes orientated parallel to the XZ-plane and YZ-plane.

Similar to the cylindrical bounding of the filament, intersection with the cylindrical section of the quartz surface is evaluated using a 2D circle in the XY-plane (Fig. 7.6a and b). The intersection between the top and bottom hemispheres is determined using the equation of a sphere:

$$x^2 + y^2 + (z - z_{hemisphere})^2 = r^2 \quad (7.9)$$

The variables x , y and z , can again be substituted for the parametric representations provided in Eq. 7.7. The variable $z_{hemisphere}$ is the position of the origin of the sphere on the z -axis. The solutions to this problem can be pre-solved and implicitly coded into the algorithm such that only simple mathematical operations need to be performed, decreasing the runtime of the code.

If the ray intersects the quartz envelope, the probability of reflection and transmission must be determined using the Fresnel equations. The same approach as was applied to the 2D problem is adopted and can be found in 5.5.4.1 on page 115.

7.2.4.3 Supports

The position and dimensions of the molybdenum supports for the 1000 W lamp were determined by the average of several lamps measured using digital callipers. There are four supports in total, as shown in Fig. 7.8, two of which transmit the electrical current and connect to either end of the filament. The remaining supports provide mechanical fixturing to the mid-section of the filament. The curved elements of the supports are disregarded as this requires complex geometric representations to account for the structure, which would vastly increase the complexity of the intersection tests with little benefit in terms of model accuracy. For each iteration within the lamp, tests are carried out with each of the four supports using the cylindrical tracing method outlined previously.

The reflectivity data used in the model for molybdenum is provided by Zhao [168]. This is likely to be an overestimate of the reflectivity due to the polished finish of the samples tested in this study. However, there is very little data in the literature regarding the surface

properties of molybdenum, and none at all for molybdenum which has been subjected to the conditions undergone by the filament supports with the QTH lamp. Besides, it is not even clear how smooth the surface of the supports are in the as-received state, and since the supports are small and cylindrical, it is not possible to test the reflectivity using the methods previously employed in this study. Given these factors and that the influence of the support on the overall performance of the FIRH is anticipated to be relatively minor, the assumption of using the data provided by Zhao [168] is deemed reasonable.

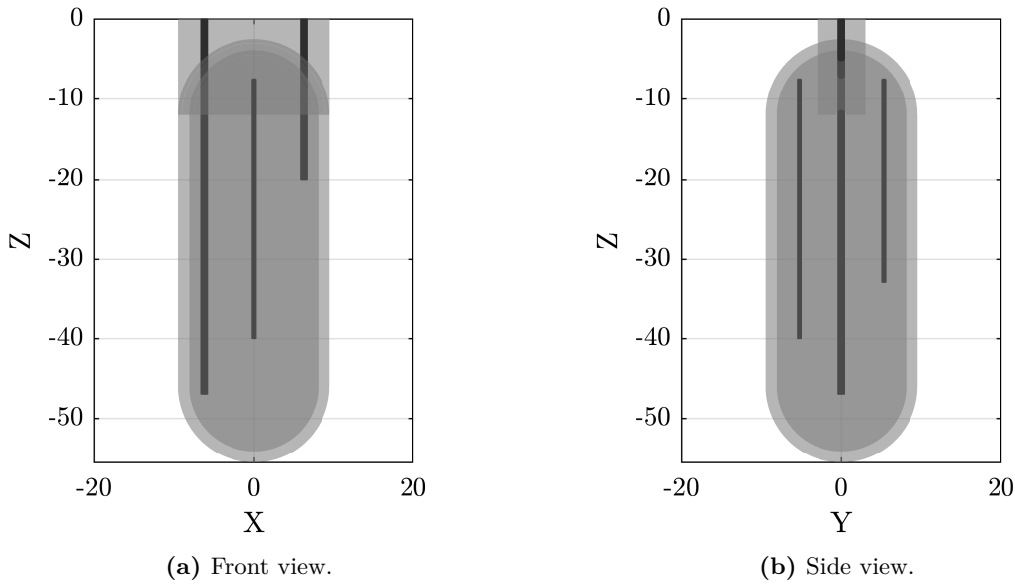


Figure 7.8: Schematic of supports for the 1000 W lamp (shown in black).

7.2.5 Tracing within the quartz envelope bulk

Within the quartz envelope, intersection tests are performed with the quartz air interfaces, including those within the quartz base. The intersection tests are performed using a technique similar to that outlined already, except that the spheres and cylinders are tested for interactions with both the internal and external radii of the quartz envelope. Once the new intersection point within the quartz has been determined, the likelihood of absorption within the quartz must be considered based on the distance travelled in 3D. This is performed using Eq. 5.19, which was described for the 2D model implementation.

7.2.6 Tracing outside of the lamp

Outside of the lamp, the intersection tests can be performed with the outer surface of the quartz envelope, the target surface, the top surface of the reflector, and the reflector walls, similar to the 2D case. The potential to reach the target surface and the top surface of the reflector are first differentiated by the direction vector of the ray. If the z-vector is positive, intersection testing is commenced with the top surface surrounding the lamp insert. Otherwise, a test is performed on the plane that corresponds to the target surface. When the intersection point has been determined, the “radius” at that point from the rotational axis (i.e. the square root of the square of the x and y components) is compared to the maximum radius of the top or target surface. If the radius is less than that of the radius of that surface, the ray is considered to intersect the surface. Otherwise, the ray must intersect the curved reflector. Determining the intersection and surface normal vector will be discussed separately in Section 7.4 after Bézier surfaces are introduced.

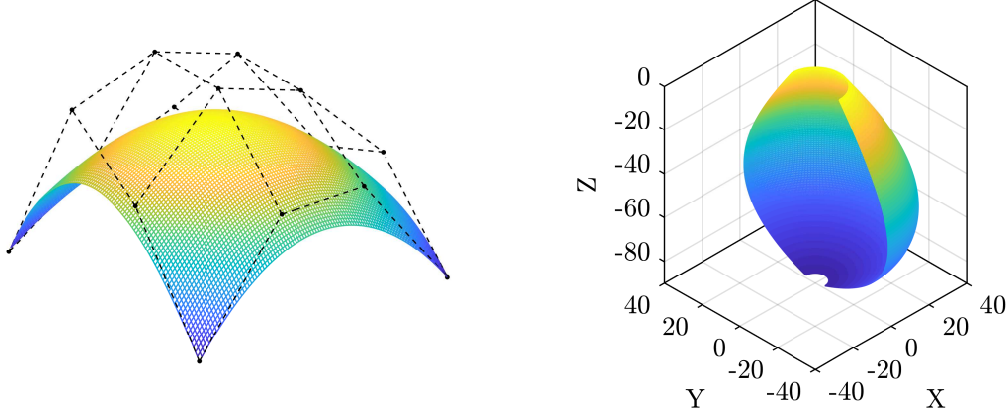
7.3 Bézier surfaces

A Bézier curve can be extended to a Bézier surface for 3D problem sets. A Bézier surface (sometimes referred to as a Bézier patch) is characterised by several of the same features as a Bézier curve: its shape can be modified trivially by changing the position of control points, the surface is flexible and can represent a wide range of shapes, it is robust, and can be extended to higher-order surfaces easily if desired. However, Bézier surfaces are more challenging to work with, principally due to the additional computational complexity associated with solving an intersection with the surface and a traced ray.

An example of a bi-cubic Bézier surface constructed using 16 control points is shown in Fig. 7.9a. The control polygon is shown in dashed lines above the surface. The number of control points for a Bézier surface is the product of the order of the curves which are used to construct the surface, i.e. for a bi-cubic surface, a 4×4 grid of control points is employed totalling 16 control points. Typically, a Bézier curve is parameterised by the variable $t \in [0, 1]$, which describes the position along the curve. For surfaces, the convention is to use parametric variables $u \in [0, 1]$ and $v \in [0, 1]$ to describe the position on the surface similar to normalised coordinates in a 2D plane.

Four identical Bézier surfaces can be used to describe quarters of the reflector which allows a close approximation of an axisymmetric geometry. Two Bézier surfaces composing a

half reflector is shown in Fig. 7.9b. Fewer than four surfaces cannot accurately approximate a circular cross-section while more than four surfaces does not provide any measurable benefit.



(a) Bi-cubic Bézier surface with the control polygon and points shown as dashed lines and dots. (b) Two Bézier curves used to construct half of the axisymmetric reflector geometry.

Figure 7.9: Bézier surfaces examples. A colour gradient is included to allow the perception of depth.

7.4 Bézier surface intersection testing

Evaluating the intersection between a line and a Bézier surface is a nontrivial problem. The two methods proposed in the literature either solve the simultaneous equation of a line and Bézier surface numerically, or use subdivision of the surface similar to that employed in the 2D model, but extended to 3D.

Any algorithm employed to find the intersection between a line and a Bézier patch must be fast and accurate. An implication of using a GA or another metaheuristic optimisation technique is that a vast number of shapes will be tested. Further, each shape must be evaluated with a large number of rays in order to reduce the statistical error associated with the MC method. Consider the following example: if one was to approximate the number of intersections required for the shape optimisation process, the population size could be estimated to be 100, the number of generations 100, and 10,000 rays traced for each shape. Each ray may also intersect the reflector more than once, but that is disregarded in this example. In this scenario, there will be at least 10^8 ray-Bézier surface intersections to be calculated for a GA based optimisation of a FIRH. If each ray intersection takes 1 second, a lower bound on the total time will be over three years, and that is excluding

any other computations the ray tracer must perform. For a computation time of 24 hours, the intersection test must be less than 10^{-3} seconds. This section will, therefore, outline methods for calculating ray-Bézier intersection and normal vector calculation with a focus on the speed of the algorithm while maintaining acceptable accuracy. Firstly, two methods from the literature will be described and tested, namely, numerical methods and Bézier surface subdivision. Then, two alternative methods developed in this work will be described and compared.

7.4.1 Numerical methods

When broken down into its direction components, the equation of a ray can be written as follows:

$$R_x(t_R) = P_x + t_R \times \vec{v}_x; R_y(t_R) = P_y + t_R \times \vec{v}_y; R_z(t_R) = P_z + t_R \times \vec{v}_z \quad (7.10)$$

where R is the new position along the path of the ray, which is a function of t_R , P is the current or known position along the ray, and $\vec{v}$ is the vector direction. The equation of a Bézier surface can be written in matrix format as:

$$S(u, v) = \mathbf{u} \cdot \mathbf{B} \cdot \mathbf{P} \cdot \mathbf{B}^T \cdot \mathbf{v}^T \quad (7.11)$$

where $\mathbf{u}$ and $\mathbf{v}$ are the vectorised coefficients, $\mathbf{B}$ is the cubic Bézier matrix (see reference [169]), and $\mathbf{P}$ is the matrix of 16 control points which defines the shape of the surface. The equation of the surface can be broken down into its components similar to the equation of a line by using the $\mathbf{P}_x$, $\mathbf{P}_y$, and $\mathbf{P}_z$ control points. Equating the components from the ray and surface:

$$S_x(u, v) - R_x(t_R) = 0, \quad S_y(u, v) - R_y(t_R) = 0, \quad S_z(u, v) - R_z(t_R) = 0 \quad (7.12)$$

This results in three unknowns of t , u , and v that can be solved simultaneously using a suitable numerical solver. However, this method was found to be extremely computationally expensive, taking almost 10 seconds per intersection test. An alternative numerical method using algebraic geometry was proposed by Kajiya [170] in work regarding Bézier patches and ray intersections for graphics applications. This method involved transforming an intersection of a ray and surface in 3D space to the intersection of two algebraic curves in complex

2D space. However, the author noted that this method was not significantly faster (described as “slow but accurate”) but was more robust than other methods proposed in the literature.

7.4.2 Bézier subdivision

Bézier curve subdivision described in section 5.5.8.2 can also be extended to surfaces, where the surface is reduced in both u and v directions concurrently. This process of subdivision in 3D is considerably more expensive to compute when compared to the subdivision in 2D. In the implementation employed in this work, a large proportion of the computation time was due to the calculation of the “quasi-interpolating polygon” [169] which encompasses a large number of simple mathematical operations (which can be carried out as a matrix operation) and is a critical part of the algorithm. This cannot be further simplified, and therefore, although minor speed increases could be achieved from the optimisation of the overall code, a significant improvement in speed of the size required for this application cannot be obtained using this algorithm. Fougere [169] proposed a modification of subdivision by using a geometric based algorithm with projections and 2D intersection tests; however, this algorithm also employs the quasi-interpolating polygon which was found to be the limiting factor for subdivision.

Neither of these methods satisfies the requirement for a fast algorithm which can process 1000’s of Bézier-ray intersections per second. Therefore, an investigation into a method which can enhance the speed of the intersection tests was undertaken. This led to the development of two approaches which will be referred to as the “vector dot product minimisation” (VDPM) and “radial difference minimisation” (RDM) algorithms.

7.4.3 Vector dot product minimisation

The vector dot product minimisation (VDPM) method is an algorithm developed with the assumption of the intersection between a concave, nonoverlapping Bézier surface and a ray. In short, intersection testing is achieved by minimising the difference between the vector direction of the ray and the vector between the ray origin and the potential set of intersection points. The steps to this algorithm are as follows:

1. The discretisation of the Bézier surface into a grid of potential interception points.
The number of points should be chosen so that sufficient accuracy is achieved, but not so large that the algorithm is overly computationally expensive. This is the classic

balance between the size of the grid and the speed of the solver when modelling a problem using numerical discretisation.

2. The vector between the current intersection point and the potential interception points is determined using the standard definition of a vector:

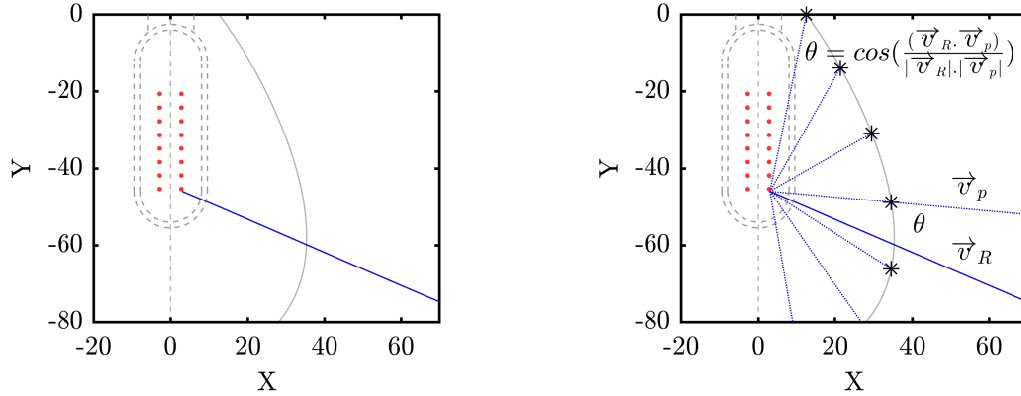
$$\vec{v} = P_{potential} - P_{current} \quad (7.13)$$

This creates a matrix of vectors which correspond to each potential interception point on the Bézier surface.

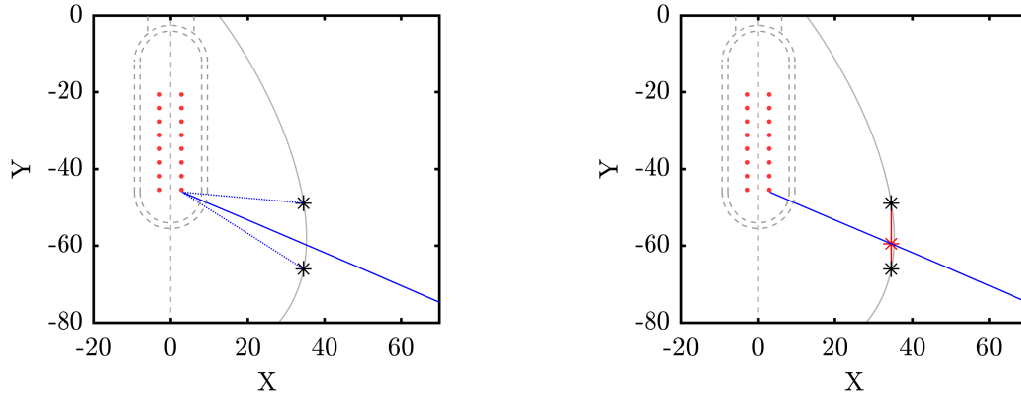
3. The vectors within the matrix are normalised to a unit length.
4. The dot product is computed between the vector direction and each potential vector in the matrix. The dot product is a measure of the angle between each potential vector and the actual vector.
5. The vectors with the smallest angle are selected.
6. A 2D interpolation is employed to allow intersection points to be found in between the grid points.
7. The normal vector at the intercept location is determined based on the cross product of the grid points surrounding the interception point.

An illustration of the VDPM algorithm is provided in Fig. 7.10 in 2D for clarity, however, this can be extended to the 3D case with no modification to the underlying principles. A recursive method is employed, where the process is first carried out on a coarse mesh, before refining the interrogation in the area of interest.

The VDPM method is significantly faster than the numerical method or Bézier surface subdivision; however, it compromises on accuracy unless an excessively large number of grid points are used. This method assumes that the shape is made up of a series of flat “tiles” with discontinuities of both the surface and normal vector at the grid point connections. This is in contrast to the actual Bézier shape, which is a continuously varying curved surface. The accuracy of the VDPM method and continuity of the represented shape could also be increased by using a 2D spline interpolation. However, the implementation of this in a robust manner proved challenging for the author.



(a) A ray passing through an arbitrary Bézier curve. (b) Division of the Bézier curve and determining the angle between the potential intersections.



(c) The two smallest angle points are selected. (d) Interpolation to find the final intercept location.

Figure 7.10: Illustration of the VDPM algorithm.

7.4.4 Radial difference minimisation

The search for a fast and accurate Bézier-ray tracing algorithm is assisted by the fact that the shapes investigated in this research are axisymmetric. This implies that the problem can be simplified to negate the need to model the reflector using four separate surfaces, and instead can be represented using a single 2D axisymmetric curve. Nonaxisymmetric components (such as the lamp supports, sections of the quartz envelope) can still be traced in 3D. The approach of reducing an axisymmetric shape to a 2D representation during ray tracing is similar to that employed by Feldick and Modest [171]. The essence of this axisymmetric simplification is that at the intercept location on the Bézier curve, the square root of the squares of the x and y coordinate (i.e. the radius from the axis of rotation) must equal the

radius of the Bézier curve at that z-coordinate:

$$r_{ray} = \sqrt{x^2 + y^2} \quad (7.14)$$

The radial location of the ray at a given height can be compared to the radius of the Bézier surface at that height, and the intersection between the ray and surface occurs when the difference between these two radius values is zero. The following procedure is performed in this algorithm for the calculation of the intersection point:

1. A z-coordinate to Bézier radius lookup table is created during initialisation of the MCRT algorithm. This table contains the radius of the Bézier curve across the range of heights which the Bézier curve spans. For the implementation used in this work, a total of 10,000 coordinates and corresponding radii were listed in the table, which divided the curve into lengths of $\sim 10^{-2}$ mm.
2. The parametric t_R value for the ray being traced is determined for each of the z-heights in the lookup table.
3. The x and y coordinates of the ray are determined for each of these t values
4. The radius of the potential intersection point along the path of the ray is determined using Eq. 7.14.
5. At each height, the difference between the radius of the ray is compared to the radius of the Bézier surface.
6. The height where the difference between these two values is zero is found through interpolation.
7. The x and y coordinates are recalculated based on the final interpolated height using the equation of a line.
8. The normal vector is determined through the cross product of the tangent vector on the circular cross-section and the vector formed by the two grid points adjacent to the intercept location. The former is the horizontal tangent on the surface at the intersection point, while the latter is the vertical tangent. Both tangent vectors should be normalised before computing the normal vector using the cross product.

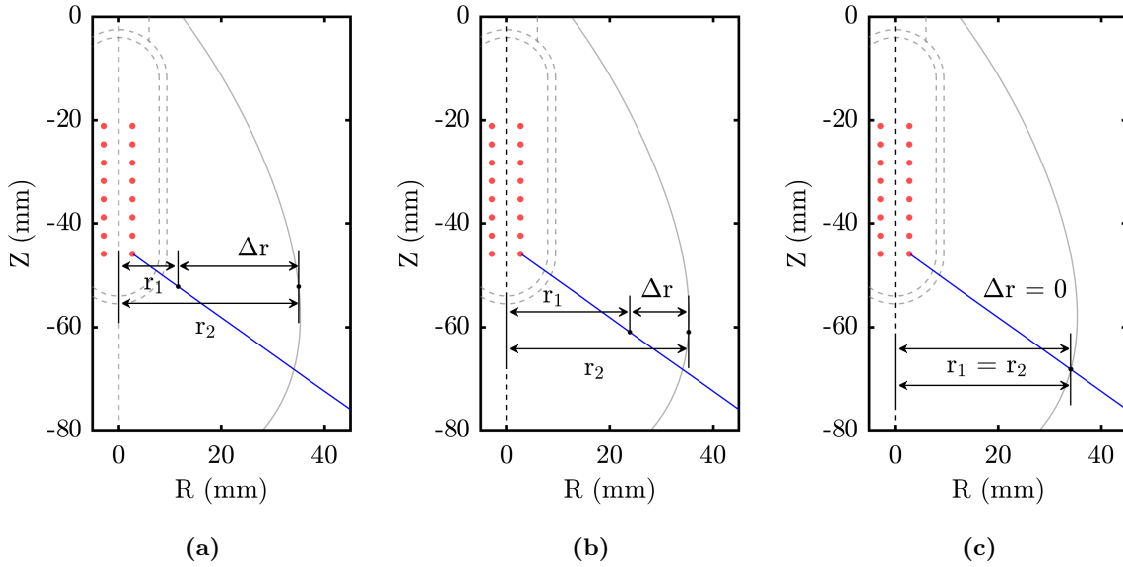


Figure 7.11: Illustration of the RDM method broken into three steps demonstrating convergence upon the intersection point. r_1 is the distance from the rotational axis to a given point on the ray, and r_2 is the distance from the rotational axis to the Bézier surface at the same height. The difference between the two radii, Δr , is minimised where the ray intersects the Bézier surface.

$$\vec{N} = \vec{T}_1 \times \vec{T}_2 \quad (7.15)$$

$$\vec{T}_1 = [y, -x, 0]; \vec{T}_2 = [x'_2, y'_2, z'_2] - [x'_1, y'_1, z'_1] \quad (7.16)$$

An illustration of the RDM method is shown in Fig. 7.11. Similar to the VPDM algorithm, a recursive technique is used where a coarse grid of points is first examined, followed by a finer investigation within the area of interest. The accuracy can easily be tuned to an appropriate level, much like Bézier subdivision or the VDPM method.

This algorithm finds difficulty in determining the intersection between a ray and Bézier surface when the z-vector is close to zero. This is due to the resolution of the grid and that at small z-vector values the ray may not pass through any grid points. In this case, it is assumed the z-vector is zero and that the problem can be solved in 2D via the intersection of a line with a circle.

7.4.5 Comparison of Bézier-ray intersection algorithms

A log plot comparison of the function call time and error for the four Bézier intersection algorithms is shown in Fig. 7.12. This was generated by testing each method with 1000 ray intercepts with an elliptical shape defined using a Bézier curve. The MATLAB code profiler

was used to find the call time for each algorithm. The error is defined as the difference between the actual interception point and the interception calculated by a given algorithm divided by the distance travelled by the ray. The numerical solver was assumed to find the actual intersection point (within rounding errors), and therefore the error is specified as zero.

The figure shows that the numerical solver requires almost two orders of magnitude longer to solve an intersection than the Bézier subdivision method, with a total time of almost 10 seconds per function call. At this speed, a single optimisation iteration would require decades with modern computational power from a desktop PC. At the resolution selected, the Bézier subdivision is significantly slower than the VDPM strategy while delivering a similar level of error. Comparing the two methods developed in this work, the VDPM method requires a comparable computation time to the RDM method, but the RDM method delivers an error that is four orders of magnitude lower.

The RDM method shows the best all-round performance. Although this may not be a general algorithm that can be applied to any 3D problem, it has the best balance of accuracy, speed and robustness for this particular task and therefore is the algorithm that will be used going forward. It is noted that higher resolution could be obtained using both the Bézier subdivision and VDPM method; however, this would require more iterations or grid points, which would further increase the computational requirements.

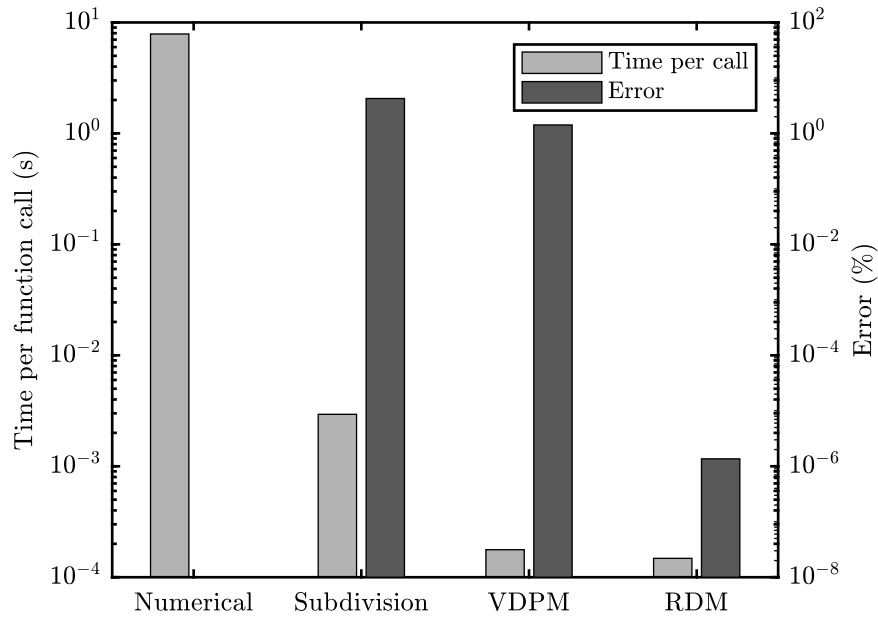


Figure 7.12: Comparison of the run time and error for the various intersection algorithms.

7.5 Validation of the MCRT model

Given that this is a bespoke RT model, the code must be rigorously validated to ensure that the model is representative of the physics underlying the operation of FIRHs. The 3D model is validated using three techniques:

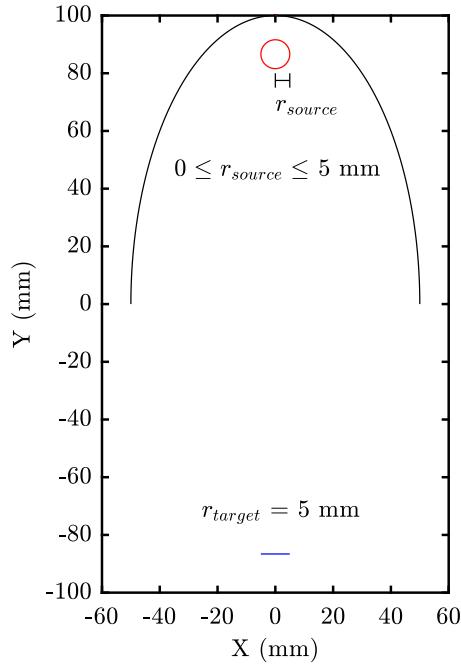
1. First, the MCRT algorithm is compared to the commercial RT package TracePro by examining an ellipse under various source position and size conditions.
2. The experimental power output of the FIRH described in Chapter 6 is compared to the 3D MCRT model for both the Al and Au reflector types.
3. The final validation is a comparison between the MCRT model and experimental measurements of the heat flux distribution emanating from an open reflector.

7.5.1 Comparison between the MCRT algorithm and TracePro

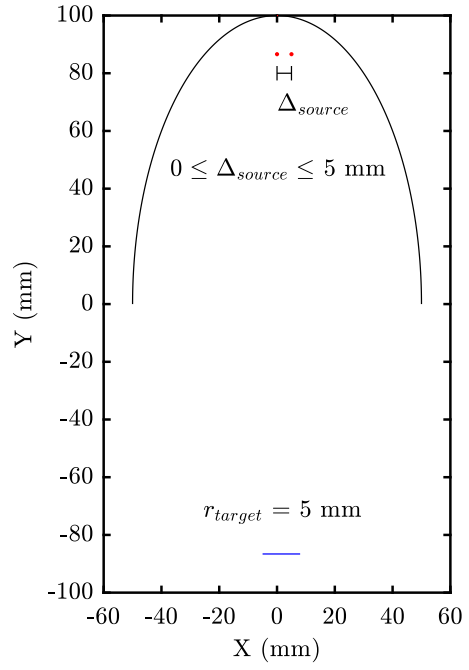
A comparison of the MCRT model developed in this work to a commercial RT package allows the validation of the ray-Bézier intersection algorithm, the normal vector calculation on the surface of the reflector, the new vector direction calculation, and the Lambertian source distribution function. Each of these aspects of the model impacts the combined ray paths produced by an ellipse and therefore must be accurately implemented for agreement to be demonstrated. The setup for this validation is shown in Fig. 7.13a-b. For the first test, the radius of the spherical source is varied between 0 and 5 mm while its centre is located at the focal point of a semiellipse with a 100 mm major axis and a 50 mm minor axis, as shown in Fig. 7.13a. Secondly, a point source is moved radially from the focal point of an ellipse of the same dimensions, as shown in Fig. 7.13b. The efficiency is defined as the ratio between the number of rays that intercept the 10 mm diameter target surface compared to the total number of rays emitted from the source:

$$\eta_{ref} = \frac{N_{target}}{N_{total}} \quad (7.17)$$

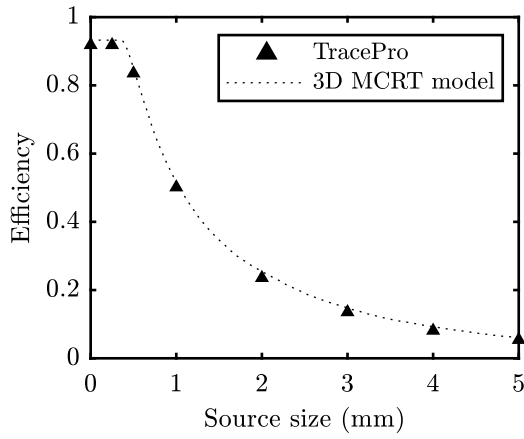
The ellipse surface is assumed to reflect 100% of the incident rays specularly, and 10,000 rays were employed for each test. Figures 7.13c and d show the comparison between the MCRT algorithm and TracePro for the two tests performed. Both tests show agreement across the entire range of conditions.



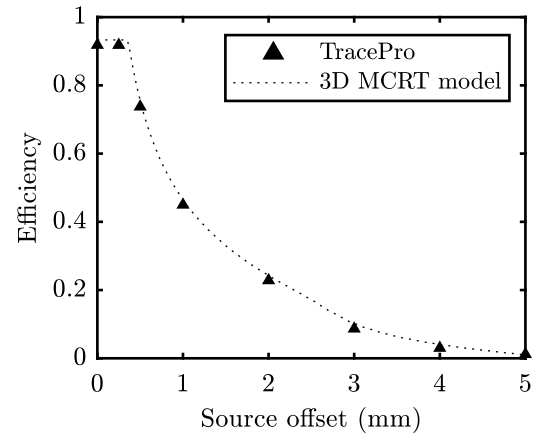
(a) Variable source radius.



(b) Variable position point source.



(c) Varying spherical source radius.



(d) Varying point source position.

Figure 7.13: The validation setup for the 3D model (shown as a 2D cross-section) and comparison between the MCRT algorithm and TracePro for a 100-50 semiellipse.

7.5.2 Comparison of FIRH power output

The experimentally measured power output of a FIRH can also be used to validate the MCRT model. However, in order to provide context to the comparison, the uncertainty associated with the MCRT model must be estimated. Since each material property will have varying significance within the model (for example, the reflectivity of the wall will have a more significant impact on the efficiency than the reflectivity of the molybdenum supports), the uncertainty cannot be analysed using traditional statistical techniques. A second MC simulation was utilised by assigning normally distributed uncertainties to each of the input parameters (P), as depicted in Fig. 7.14. This simulation was run 100 times, and the standard deviation of the reflector efficiency and the resulting uncertainty of the model determined.

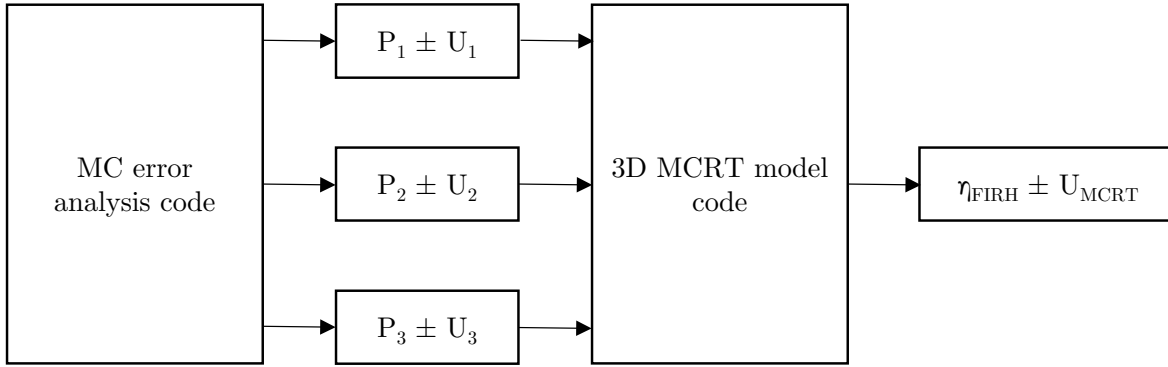


Figure 7.14: Block diagram illustration of the MCRT uncertainty analysis technique.

The estimated uncertainty associated with each of the input variables considered is presented in Table 7.1. The uncertainty of the reflectivity of the enclosure wall was estimated based on the repeatability of the reflectivity measurements ($\pm 0.7\%$) [77]. The uncertainty associated with the tungsten emissivity is challenging to estimate, given that no error analysis was provided by the author of the original research [147]. However, good agreement was demonstrated between the experimental data and Drude's law, and therefore, it is estimated to be $\pm 1.0\%$. The radiative efficiency uncertainty is estimated to be $\pm 2.6\%$ based on the analysis in section 3.2.4. The reflectivity data of the molybdenum supports assumes a polished surface, which is not the case for the material in this work. Consequently, the uncertainty is estimated to be $\pm 10\%$ to compensate. Good agreement is exhibited for absorptivity of the quartz in the literature; however, since the quartz properties of the lamp used in this work have not been tested, the uncertainty is estimated to be $\pm 5\%$. Each simulation traced 250,000 rays to reduce the statistical error from the MCRT analysis to $< 1\%$. The details of how this number was found will be described in section 7.6. The distribution of the

efficiencies obtained from this analysis is shown in Fig. 7.15 with an estimated uncertainty of $\pm 4\%$ for the Al reflector and $\pm 7\%$ for the Au reflector. The discrepancy of the uncertainty between the two reflector types is due to the more significant effect of the uncertainty of the reflectivity of the wall on the efficiency at higher reflectivity values. For example, a 0.7% change has a more considerable impact on the efficiency of a $\sim 96\%$ reflective surface for Au than $\sim 88\%$ for Al due to the compounding effect of multiple reflections within the FIRH.

Table 7.1: Estimated uncertainty for the material properties employed.

Wall reflectivity	Tungsten emissivity	Radiative efficiency	Reflectivity molybdenum	Absorptivity quartz
$\pm 0.7\%$	$\pm 1.0\%$	$\pm 2.6\%$	$\pm 10.0\%$	$\pm 5\%$

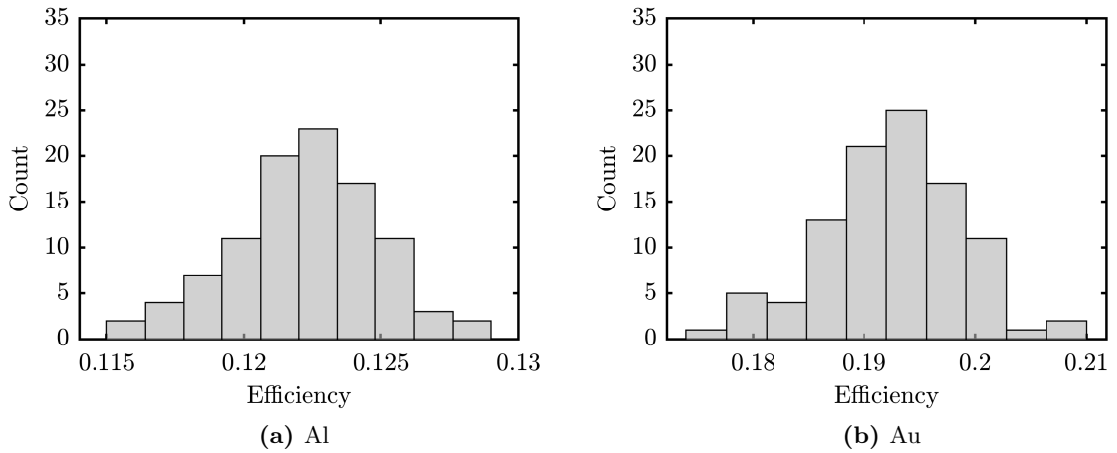


Figure 7.15: Reflector efficiency uncertainty derived from 100 simulations.

Fig. 7.16 shows the comparison between the experimental measurements and the two model predictions. Both predictions for the Al and Au reflectors agree reasonably well with the experimental measurements, with a 7% and 3% difference respectively. Given the difficulty in characterising the curved reflective surfaces of the enclosure wall and the experimental uncertainty surrounding the quartz envelope properties, the model is deemed to predict the efficiency of the FIRH adequately. The uncertainty of the power measurements has been estimated to be 5% based on the calibration carried out on the power meter, which can be found in Appendix C.2.

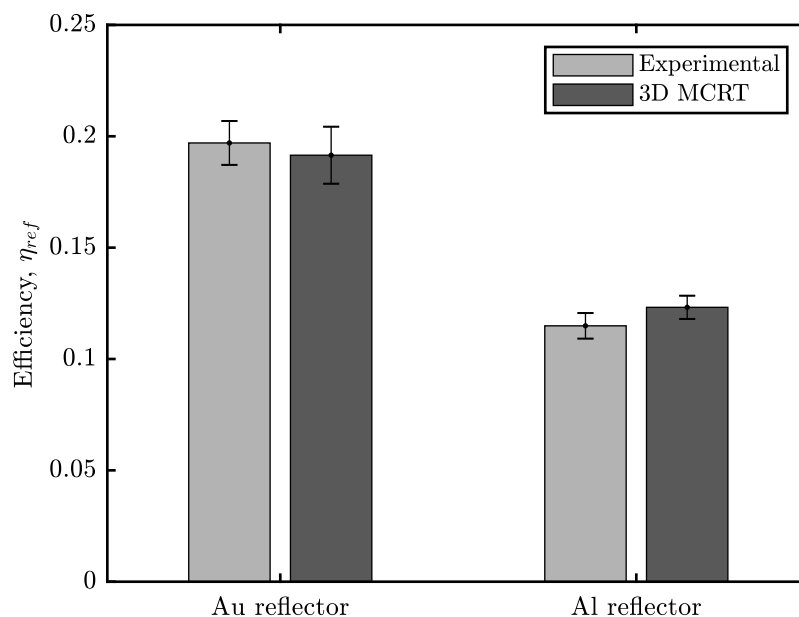


Figure 7.16: Comparison between the experimental measurements and the 3D MCRT model prediction for the 2D GA optimised units with 95% confidence interval error bars.

7.5.3 Comparison of heat flux output distributions

The open shape used to validate the MCRT model consisted of a truncated version of the 2D optimised GA heater, where 20 mm from the bottom of the reflector was removed to provide a 33 mm diameter outlet. This shape was chosen since it is a modified version of the previous FIRH design, and thus an entirely new shape did not need to be designed. The heat flux sensor employed in the investigation has a low heat flux threshold of only 5 W/cm², and therefore it is essential to measure a heat flux output which is not concentrated over a small area but instead is widely distributed. This allows the heat flux levels to be maintained within the calibration range of the sensor. The truncated version of the optimised reflector shape meets this requirement.

The experimental procedure consists of measuring the heat flux output of the FIRH on a 50 mm × 50 mm plane below the exit of the reflector at distances of 90, 110, and 130 mm. The plane was divided into a grid with 2.5 mm spacing, resulting in 400 measurements, which can then be compared to the prediction from the 3D MCRT model. A schematic of the experimental setup is shown in Fig. 7.17.

Fig. 7.18 shows the comparison between the experimental measurements (a, c, and e) and the MCRT model prediction (b, d, and f) for the various plane heights investigated.

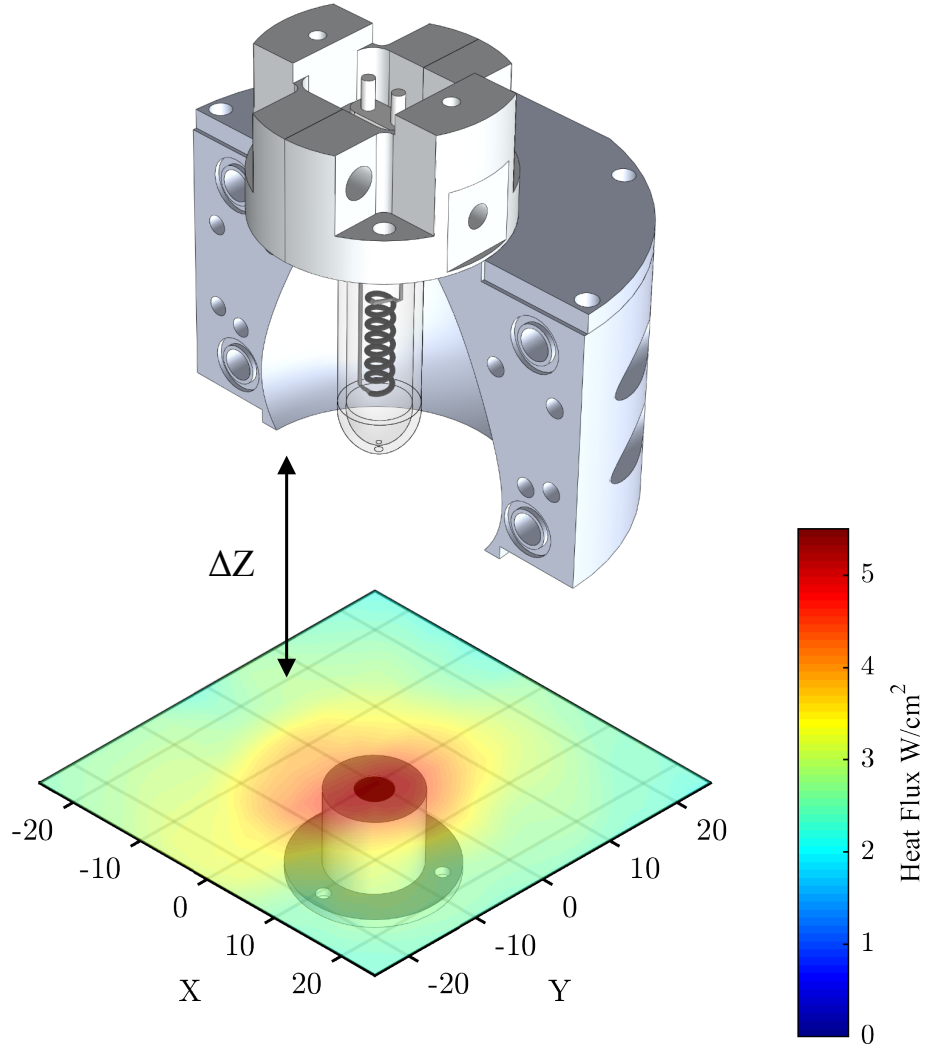


Figure 7.17: Schematic of the open shape planar heat flux measurement setup and an example heat flux map. Only one half of the reflector is shown for clarity.

The experimental measurements and the model correspond well at each of the three plane heights on an average heat flux basis. At a distance of 90 mm from the bottom of the reflector, the average heat flux for the experimental measurement over the $50 \text{ mm} \times 50 \text{ mm}$ area was 3.00 W/cm^2 , and for the MCRT model, it was 3.11 W/cm^2 , which is within $\sim 3\%$. Similar differences are observed for the 110 mm and 130 mm measurement conditions. This difference can be accounted for by the uncertainty of the experimental heat flux measurement (estimated to be $\pm 2.3\%$ by the heat flux sensor calibration report), or other uncertainties previously discussed in section 7.5.2 regarding the MCRT model.

There is a higher peak intensity predicted from the MCRT model than was experimentally measured for both the 90 mm and 110 mm distance test, which may be due to a higher diffuse reflectivity of the buffed surface than was specified in the model. A higher diffuse reflectivity

is potentially due to the reflector surface being concave and therefore more difficult to finish when compared to the flat samples characterised for reflectivity. However, both the 90 mm and 110 mm distance test demonstrate comparable overall distributions with an elliptical area of high flux extending in the positive and negative y-direction. The elliptical heat flux distribution is considered to be due to the presence of the lamp supports which will reduce the flux reaching some outer areas of the measurement plane. The 130 mm distance tests also demonstrate similar features with the high heat flux regions extending further along the y-direction; however, the overall distribution begins to show differences at this distance.

The disparity in the overall heat flux distribution may be attributed to several factors such as the positioning of the lamp within the reflector, the effect of neglecting some aspects of the lamp construction (for example, portions of the filament supports), or the other assumptions made during the modelling process. Although there are some differences between the model and experimental measurements, the model is deemed sufficient for optimising a FIRH.

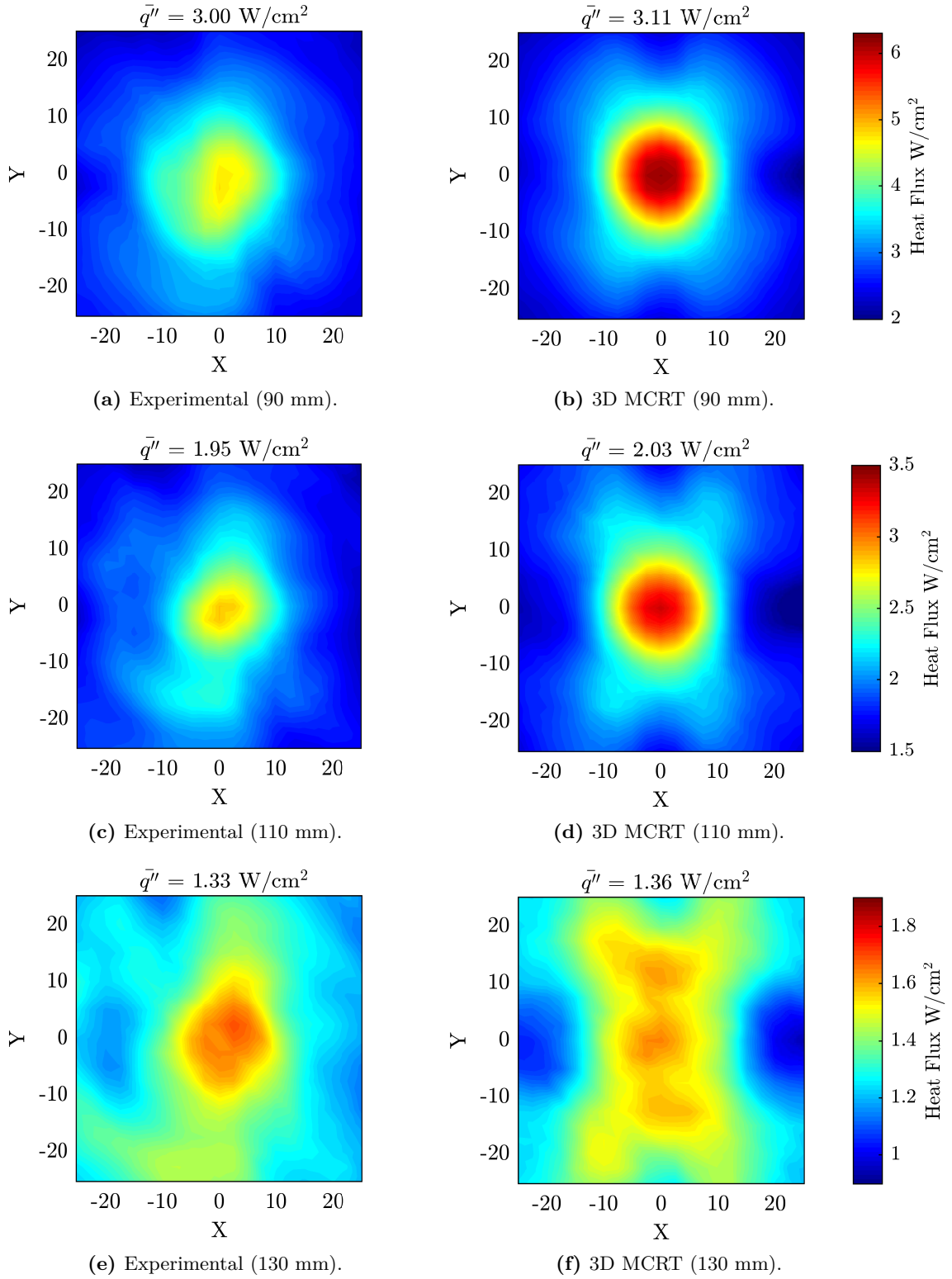


Figure 7.18: Comparison of the experimental and MCRT model heat flux distributions on a 50 mm × 50 mm surface below the reflector. Five million rays were employed for the MCRT simulation.

7.6 Monte Carlo runtime reduction

The runtime of the MCRT model must be optimised to balance overall computation time and statistical variance. This is similar to the process of a mesh refinement study for a discretised domain. The runtime reduction was carried out on the optimised FIRH developed in Chapter 6 using an approach similar to that adopted by *Cheng et al.* [121]. This process involves measuring the statistical variance of the efficiency prediction while varying the numbers of rays simulated. Fig. 7.19 shows how the statistical variation changes with the number of rays for the optimised FIRH. Each test point below 100k rays was simulated 100 times, while above this number, ten runs were utilised due to the long computation time associated with the simulation of a large number of rays. After which, the maximum, minimum, and mean efficiencies were determined for each of these number of rays. The 95% confidence interval (CI) for the efficiency at each simulation point is plotted on the secondary y-axis of Fig. 7.19 for comparison.

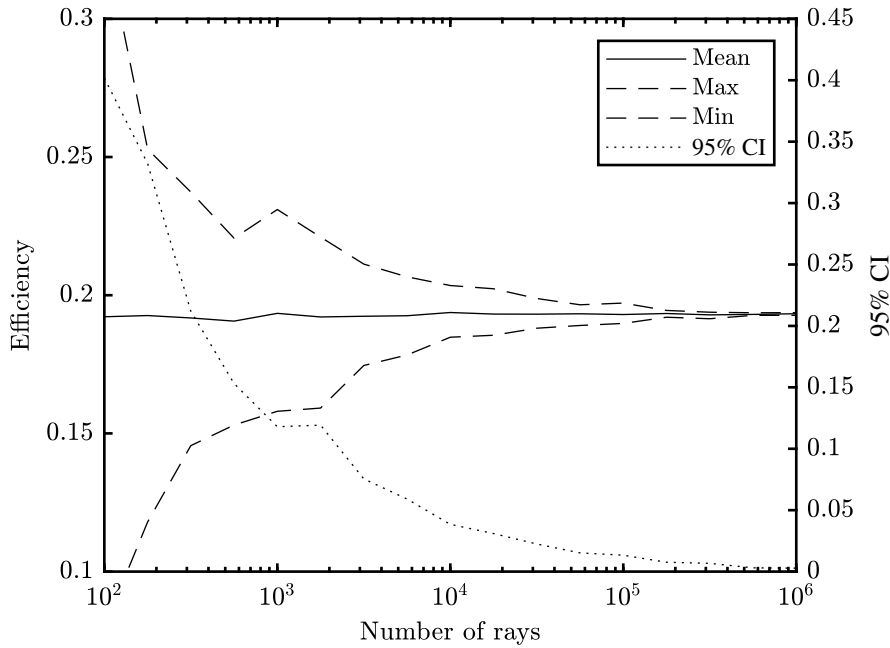


Figure 7.19: MC runtime reduction showing the statistical error for up to 10^6 rays.

It is evident that increasing the number of simulated rays reduces the statistical variance. At $\sim 10,000$ rays, the 95% CI is $\sim 4\%$ of the predicted efficiency value, which is deemed sufficient for this work when optimising the FIRH. Ideally, the number of rays would be selected such that the 95% CI was less than 1%; however, this would require the tracing of 250,000 rays which is not computationally feasible given the vast number of shapes which need to be examined. The final optimised shape will be run with 250,000 rays after the optimisation is completed to obtain a more accurate efficiency prediction.

7.7 Optimisation of the GA settings

According to *Dao et al.* [172], there are nine parameters of a GA solver which can significantly affect its performance, which are as follows: population size, fitness scaling function, selection function, elite count, crossover fraction, mutation function, crossover function, migration direction, and hybrid functions.

For nine parameters (each with at least two or four settings) the number of potential trials is unwieldy. This can be reduced by using the experimental design methods proposed by Genichi Taguchi [173], which condenses the number of trials required to more manageable sizes. The Taguchi technique uses tables called orthogonal arrays (OA), which represent the smallest fractional factorials for a given number of parameters. Although this reduction method implies that some of the second-order interactions cannot be accounted for, it allows the main effects to be analysed in a time-effective manner. *Dao et al.* [172] outlined this method for use with a GA, and the same approach will be used in this work but with minor variations.

Firstly, no hybrid function will be used as this adds significantly to the computation time without providing substantial improvements in the fitness value. Further, since this is a constrained problem with bounds on the potential solutions, the mutation function cannot be considered since “adaptive feasible” is the only function suitable for constrained problems in the current MATLAB implementation. It has been widely established that the population size plays an integral role in the performance of a GA, with higher population sizes leading to improved solver performance [174]. The computation time is also directly influenced by the population size. Therefore, this will be analysed separately in a univariate manner after the remaining variables have been optimised. For the trials, a population size of 50 candidate solutions will be used with 50 also set as the maximum number of generations.

Table 7.2: Experimental design of L32 (2^{14^6}) trials for the GA optimisation.

Parameter	Code	Level			
		1	2	3	4
Migration direction	A	Forward	Both	-	-
Fitness scaling function	B	Proportional	Rank	Top	Shift linear (rate =1)
Selection function	C	Uniform	Tournament	Roulette	Stochastic uniform
Elite count	D	1	5	10	15
Crossover fraction	E	0.3	0.5	0.7	0.9
Crossover function	F	Single-point	Two-point	Arithmetic	Scattered

The simulations were run five times each for 160 optimisation trials in total. Table 7.2 shows the list of the solver parameters for the L32 OA and their experimental levels.

The crossover function, elite count, and crossover fraction were found to have the most significant influence on the performance of the GA, as shown in the Pareto plot in Fig. 7.20. The remaining variables were found not to have as strong of an influence, but the best performing solutions from this analysis will still be used. The ANOVA table for this analysis can be found in Appendix C.1, and the optimised GA settings have been provided in Table 7.3.

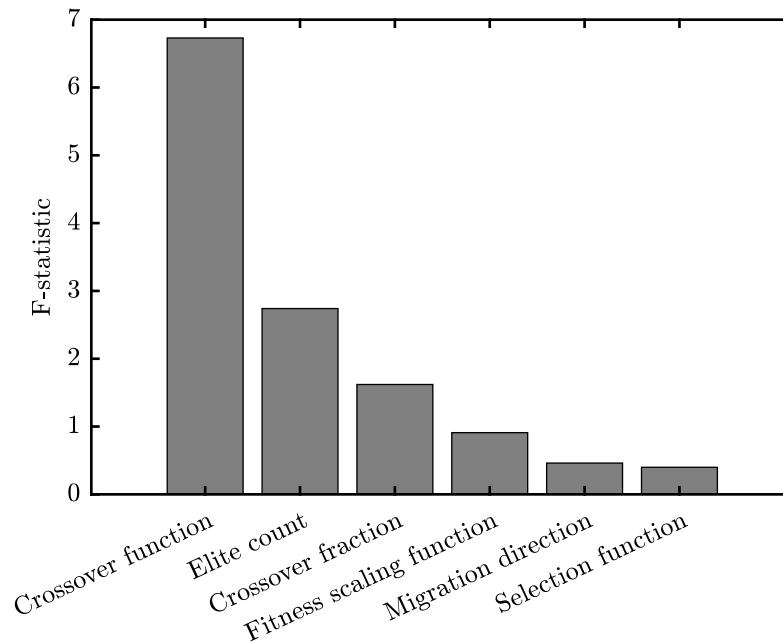
**Figure 7.20:** A Pareto plot of the Taguchi analysis results.

Fig. 7.21 shows how the performance of the GA solver varies with population size. Ten runs were tested for each population size of 500 or below, and above this number three runs were used. The highest efficiency from each of the runs at the various population sizes is shown as a dashed line. Comparing Fig. 7.21a to h, it is clear that as the population size is increased, the GA converges on a single optimum more readily. When the population size is small, convergence upon many local optimums occurs resulting in a wide variety of reflector shapes. At a population size of 500, each reflector is roughly equal in overall shape, with only minor differences in the length and width. The variance of the efficiency of the optimised reflectors is reduced as the population size is increased: with a population size of ten, the average efficiency found is $19.2 \pm 3.3\%$ whereas, for a population size of 500, the average efficiency is $23.5 \pm 0.75\%$. Population sizes of 1000 and 2500 were tested with a smaller number of runs to verify that no significant increase in performance was delivered while using these settings. It was not possible to test 1000 and 2500 population size during the actual GA optimisation due to computational power restrictions. Therefore, a population size of 500 was chosen as it can be assumed that a near-optimum solution will be found even when only a single GA run is employed. It is noted that smaller population sizes do return reasonable results as there is a progressive increase in optimiser performance as the population size is increased. This indicates that smaller population sizes may be reasonable for preliminary optimisation runs or where computational power is more limited than in this study.

Table 7.3: Optimised GA settings.

Population size	Migration direction	Fitness scaling function	Selection function	Elite count	Crossover fraction	Mutation function	Crossover function
500	Both	Proportional	Roulette	15%	0.7	Adaptive feasible	Two-point

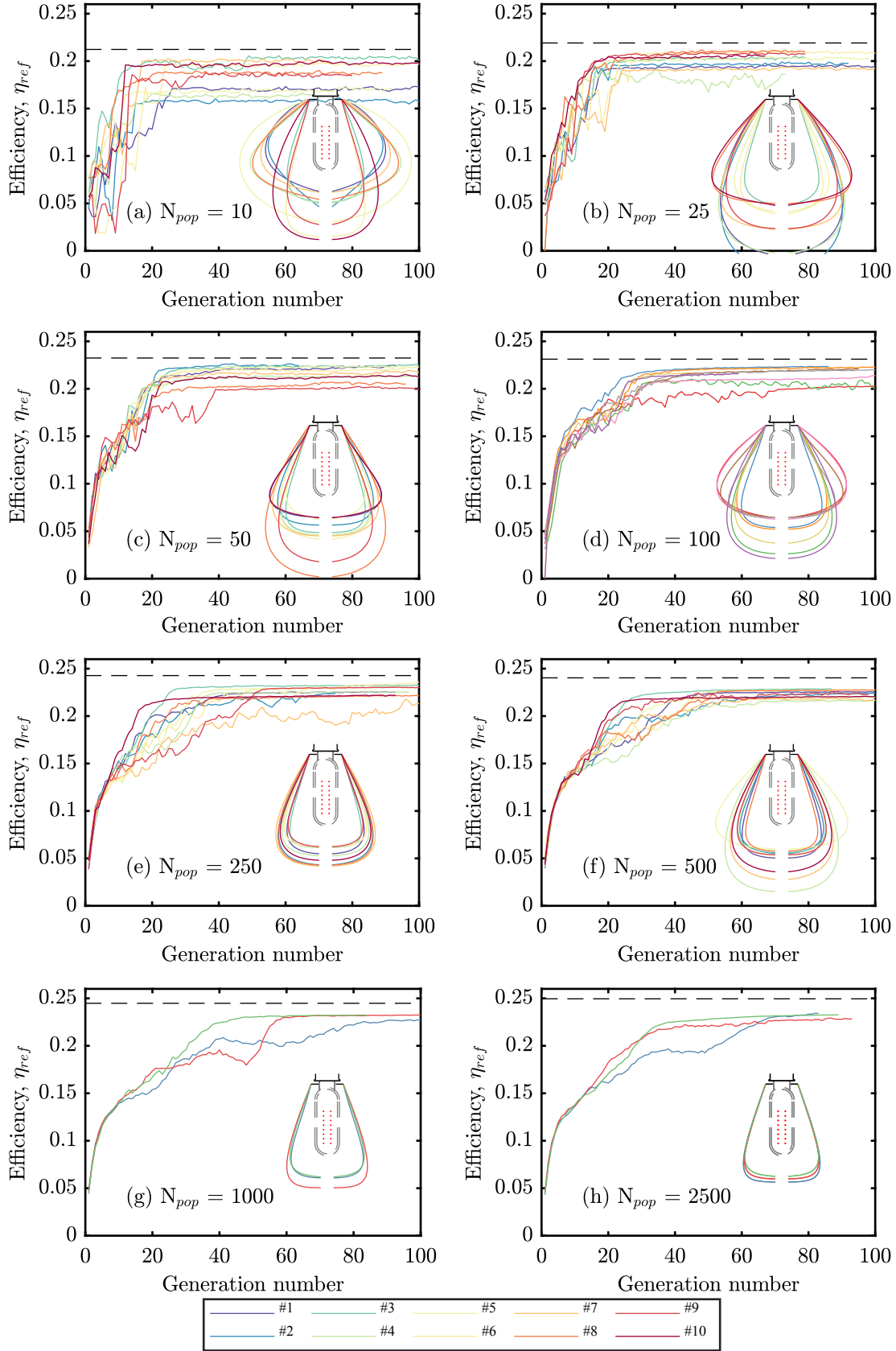


Figure 7.21: The effect of population size on the convergence of the GA showing the progression of the average efficiency of the population at each iteration.

7.8 Conclusions

The development of a 3D MCRT model which follows on from work presented in Chapter 5 has been detailed. The main conclusions which can be drawn from this chapter are as follows:

The ray tracing procedure and implementation of the 3D code were described. Many of the same strategies used for the 2D model were redeployed but adapted for a 3D case. The methods for finding the intersection between the surfaces of the quartz, supports, and filament were described using primitive 3D solids, the vectorised equation of a ray and numerical solver methods. A new Bézier ray intersection algorithm was developed, which is sufficiently fast and accurate to be used in this work for testing thousands of Bézier-ray intersections per second. The algorithm is at least two orders of magnitude faster than the methods implemented from the literature.

The 3D model developed was rigorously validated and shown to accurately predict the output of the FIRH, indicating that the modelling strategy employed is suitable for this problem type. The error associated with the model predictions was estimated to be less than 7% based on the uncertainty analysis of the data input into the model. A MC runtime reduction was performed, and 10,000 rays were found to provide a sufficiently low statistical error for use in this work.

The GA based optimisation process was investigated using the Taguchi experimental design method to determine the most suitable settings for this solution domain. The population size of the GA, crossover function, elite count, and crossover fraction are parameters that have been shown to influence the result of the optimisation process strongly. With a small population size, the optimisation process is prone to becoming trapped in local optimum and in many cases cannot find the global optimum. For a cubic Bézier curve, a population size of 500 was found to consistently deliver a near-optimum solution.

Chapter 8

Design of 3D FIRHs

8.1 Introduction

In this chapter, the 3D MCRT model is employed to optimise a range of axisymmetric reflectors. The development of a custom reflector is detailed for the 1000 W source analysed earlier in this work, and two alternative sources employed in commercially available FIRHs. The effect of the dissimilarity of the étendue and skewness between the source and target is highlighted as well as the implications of this on the performance of a FIRH. Furthermore, a design process for specifying the outlet size of a FIRH based on the concept of a “dilution-optimised” reflector is introduced, along with a method for optimising heat flux and reflector efficiency concurrently. Finally, the adjusted theoretical limits for IR based heating devices and an outlook on the use of focused IR technology for high heat flux applications are discussed.

8.2 Optimisation with the 1000 W source

A similar design procedure to that employed in Chapter 6 will be adopted for the 1000 W FIRH using the 3D MCRT model. The 1000 W lamp studied in Chapter 3 is selected as the source, and the radiation will be focused through a 10 mm diameter outlet to allow comparison to the previous design. The first Bézier point is fixed at $[12.5, 0]$ as before and limits are placed on the height and width of the reflector to maintain an adequate distance between the reflector wall and the quartz envelope while also ensuring only reasonably sized reflector shapes are tested. The bounds for the cubic Bézier curve are illustrated in Fig. 8.1 for this optimisation process. A limit of between $1.3\times$ and $2.5\times$ the length of the lamp is applied to the overall length of the reflector, as shown in Fig. 8.1c. A minimum and maximum Bézier control point radial position of $2\times$ and $10\times$ the radius of the outer surface of the quartz is also chosen. These parametric limits will be applied to each of the reflector optimisations carried out to allow the optimisation bounds to scale with the various source sizes investigated.

As described in section 6.3.3, depending on the final machining process employed, further constraints may need to be placed on the reflector shapes to limit the steepness of the angle between the first and second or third and fourth Bézier points to prevent the development of a poor surface finish. The following work in this chapter does not place any constraints on the steepness of the reflector in order to maximise the efficiency of the FIRH. Therefore, this assumes that the final shapes can be suitably manufactured using a 5-axis milling machine

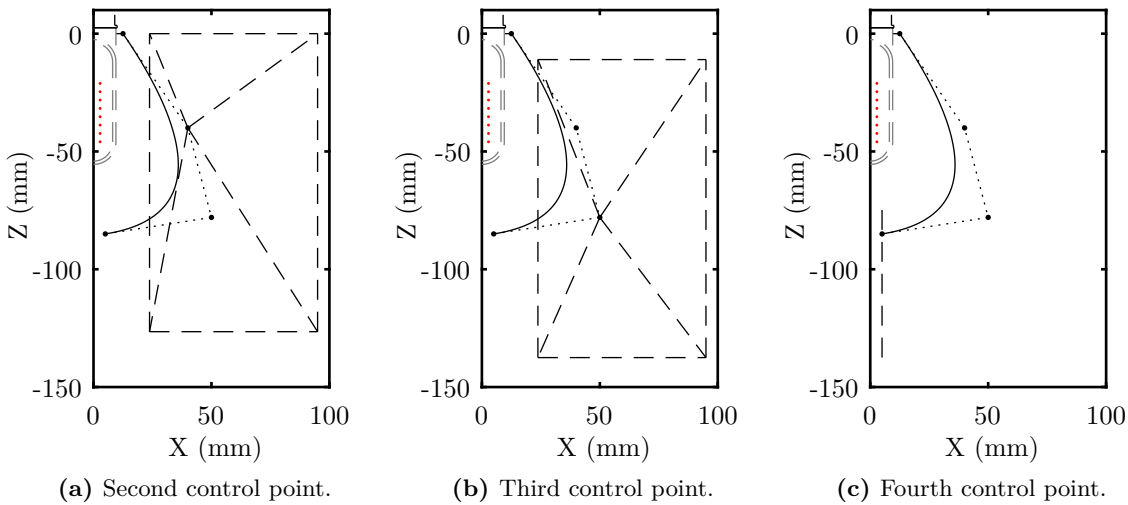


Figure 8.1: Bounding boxes placed on the control points for the 1000 W reflector optimisation process.

where these constraints are no longer an issue.

8.2.1 The effect of the order of the Bézier curve

The choice of the degree of the Bézier curve is an important consideration. Higher-order curves provide greater flexibility but are subject to continuity issues and increased computation time (due to the slower convergence of the GA). Lower-order curves are more rigid and robust but can only represent a more restricted range of shapes. Cubic curves are considered to have the best trade-off in terms of flexibility and stiffness, and as a result, are often used in CAD applications [86]. The optimal curve will depend on the specific application; therefore, this aspect of the optimisation process must be investigated.

The effect of the Bézier curve order on the efficiency of the reflectors is shown in Fig. 8.2. The use of higher-order Bézier curves marginally increases the maximum and mean efficiency of each process from the sample of ten runs for each type. However, the quartic Bézier curve exhibit appreciably higher variability than both of the lower-order curves. The standard deviation of the model predictions is nearly $3\times$ higher for the quartic curve when compared to the cubic or quadratic curve. The best performing shape for the quartic Bézier curve was 24.3% whereas for the cubic curve it was 23.3%. The additional variability when optimising a quartic curve is due to the complexity of the search domain, which is formed by seven dimensions instead of five for the cubic Bézier curve or for the quadratic curve. Despite the higher efficiency, the shapes that resulted from the quartic optimisation process were not as continuous as the cubic or quadratic curves and thus, would likely be more challenging to manufacture and finish. Constraining the quartic curve to ensure a specified level of continuity may reduce the variability and improve manufacturability. However, this was not investigated in this work but may be a potential avenue of research for future investigations.

Overall, there is very little difference between each of the curves in terms of mean efficiency for the ten runs. The repeatability of the optimisation process should be demonstrated to ensure that an optimum and consistent reflector shape is found for each iteration. The variance of the optimisation process can be reduced by utilising a larger GA population size, which allows the optimum to be found more reliably. However, it was not computationally feasible to use a larger population within the timeframe of this work. Both the quadratic and cubic curves deliver similar levels of repeatability, but the cubic curve provides slightly higher efficiencies on average. Therefore, despite a marginal increase in efficiency of the reflector with the quartic Bézier curve, the cubic curve will be utilised going forward in this

work. This will give confidence that a value determined with a small number of optimisation iterations is close to the optimum for that particular Bézier curve. It can also be concluded from this that employing a lower order quadratic curve is a viable design choice for the optimisation of FIRHs where simplicity and robustness of the curve are of primary concern.

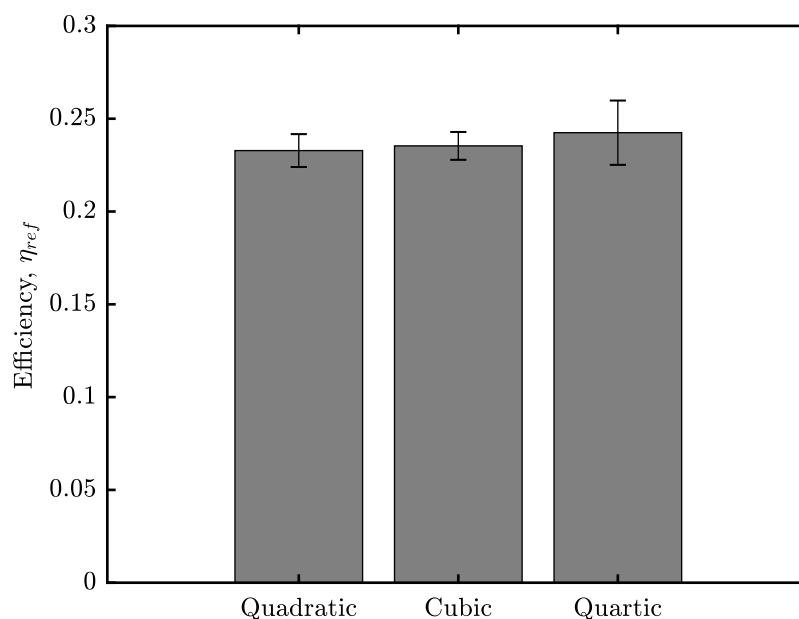


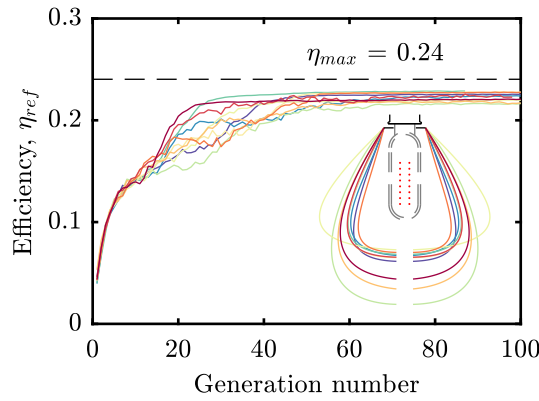
Figure 8.2: Comparison between a quadratic, cubic, and quartic Bézier curve for the optimisation of a FIRH with ten simulations for each using an Au reflector.

8.2.2 Optimisation of 1000 W source

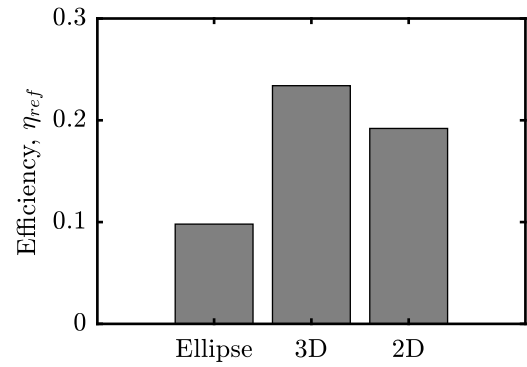
In this section, the series of optimised reflector shapes for the cubic Bézier curve with the 1000 W source will be analysed. The best-performing shape found by the optimisation process for each of the ten runs is shown in Fig. 8.3a and a comparison between the optimal shape (the best from each of the optimisations), an optimised ellipse, and the optimised shape developed using the 2D model are compared in Fig. 8.3b. Ten optimisations iterations were carried out for an Au-coated reflector, and adequate convergence was garnered as illustrated in the subplot of Fig. 8.3a. The highest performing shape found during the optimisation process had an efficiency of 24.0%, which is a considerable improvement compared to the reflector optimised in Chapter 6. The 2D shape is predicted to deliver an efficiency of 19.2% when traced with this 3D model, and therefore the 3D optimisation process delivered a $\sim 25\%$ increase in performance. The additional complexity and computational expense of the 3D

model are therefore deemed to be justified based on this enhancement in performance.

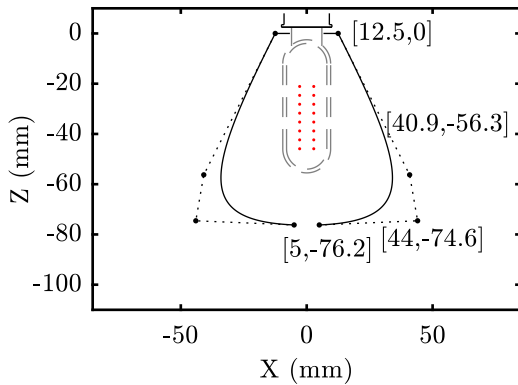
The optimised shape is benchmarked against that of an ideal spheroid (i.e. a 3D ellipse) which is found using a parametric search of the design space with the 3D MCRT model. Since the spheroid is axisymmetric, the efficiency can be plotted on a 2D efficiency map as before. The details of this simulation and the efficiency map are included in Appendix C.1; however, the most pertinent points for the 1000 W optimised ellipse are briefly discussed. A 2D comparison between the ellipse and Bézier shape is also shown in Fig. 8.4. For an Au coating, the optimised ellipse delivers an efficiency of 11% at a length and radius of 116 mm and 41 mm, respectively, although this does not take into account that the lamp protrudes from the reflector a great deal more than the reflectors defined using a Bézier shape. The optimised Bézier shape delivers over twice the efficiency with a shorter reflector size of only



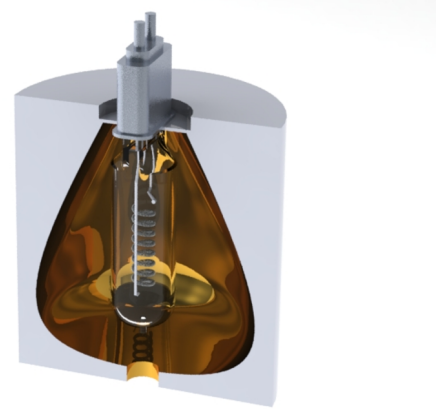
(a) Ten iterations of the 3D optimisation process for the 1000 W lamp.



(b) Comparison between the 3D optimised reflector, the reflector optimised using the 2D model and an optimised ellipse.



(c) 2D MCRT optimised reflector and an optimised ellipse.



(d) 3D view of the optimised reflector and QTH.

Figure 8.3: Optimisation of a reflector for the 1000 W source. An Au coating was used for all optimisations.

~90 mm length. This increase in efficiency at a reduced size highlights the efficacy of the optimisation process developed.

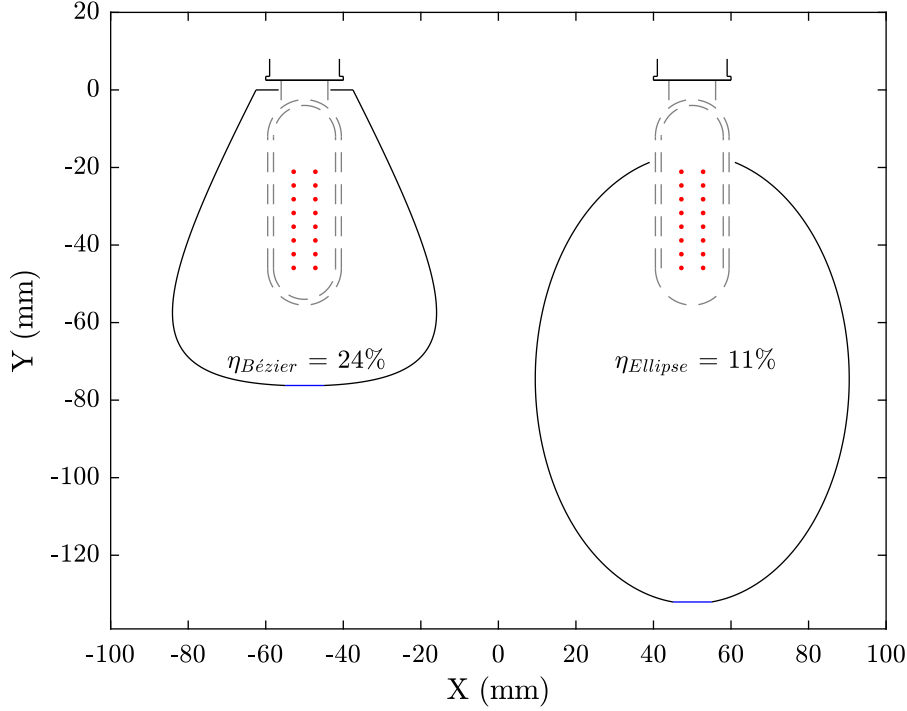


Figure 8.4: Comparison between the optimised Bézier shapes and an ideal ellipse.

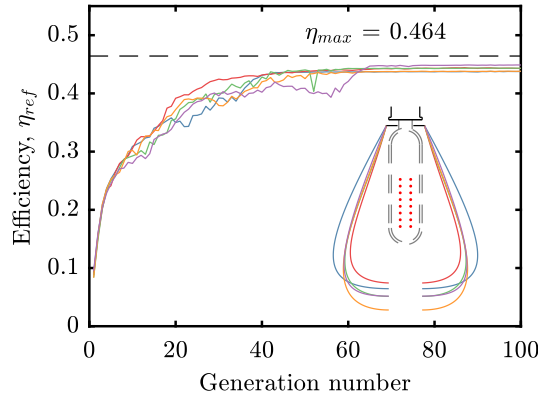
8.3 Optimisation with commercial sources

This section details the optimisation process carried out on two commercially employed QTH sources, which can be used to benchmark the optimisation process and provide context to the performance of the custom reflector shapes.

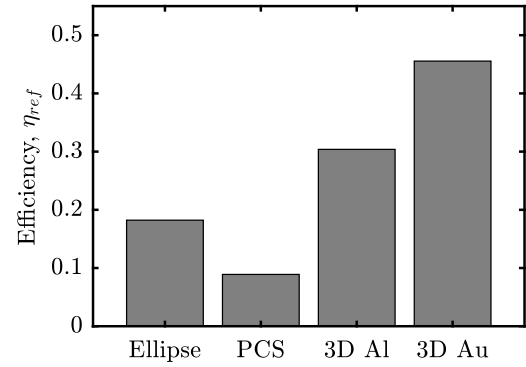
8.3.1 750 W source

The PCS SpotIR heater employs a smaller 750 W source (Ushio 120V750WEYT), which will be used as the “seed” source to develop an optimised reflector shape. For this design, the same outlet size as provided with the commercial unit (14 mm diameter) will be used as this allows a direct comparison between the performance of this unit and the optimised reflector shape developed in this work. The details of this lamp can be found in Appendix C.1, with a digitised model and dimensional measurements of the supports, filament, and quartz. The base of the quartz for this lamp is smaller when compared to the 1000 W source which means

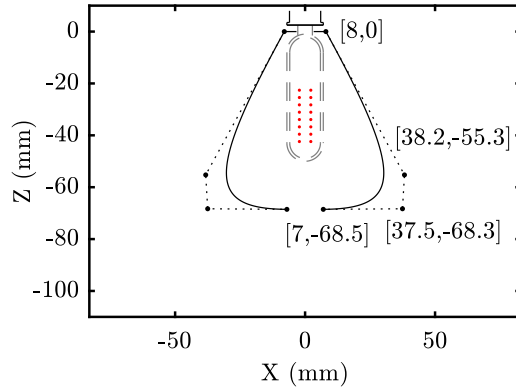
that the inlet to the reflector can be reduced from $19.6 \text{ mm} \times 6.6 \text{ mm}$ to $14 \text{ mm} \times 4.2 \text{ mm}$. This lamp is also shorter and narrower than the 1000 W lamp, and thus the reflector bounds are scaled appropriately.



(a) Five iterations of the 3D optimisation process for the 750 W lamp.



(b) Comparison between the optimised Al and Au reflectors to the PCS unit and an ideal ellipse.



(c) The optimised shape with annotated Bézier curve points.



(d) 3D view of the optimised reflector and QTH lamp.

Figure 8.5: Optimisation of a reflector with the 750 W source with an Au coating.

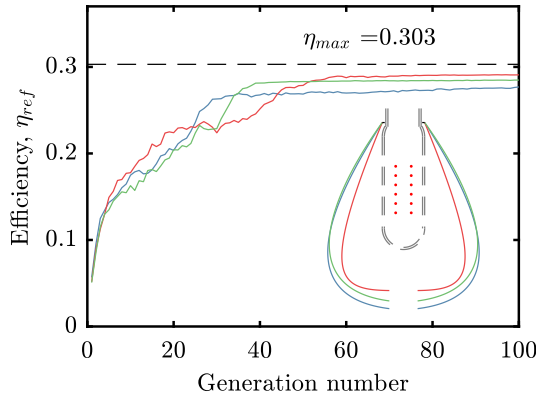
The optimisation was carried out using an Au reflector surface, but the efficiency for an Al reflector is also shown to allow comparison to the commercial device. No significant difference was observed in the final reflector shape when optimising with either an Al or Au reflector. The results of the optimisation are shown in Fig.8.5. The peak efficiency found from this optimisation process when retraced with 250k rays was 30.0% for an Al reflector. This is compared to the efficiency of the commercial unit, which was measured as only $\sim 9\%$ earlier in this work. Thus the optimisation process improved the efficiency of the device by over 200%. The Au-coated reflector delivers an even higher efficiency of 46%.

The commercial unit also performs significantly worse than the best spheroidal reflector, which is predicted to deliver an efficiency of 18%, as shown in Fig. 8.5b. This suggests that even with a restrictive elliptical reflector shape, appreciable improvements are possible for this commercial unit. The optimisation process also shows clear advantages over the ideal ellipse shape with an efficiency improvement of over 75% with a smaller reflector size. The optimisation process delivers smaller improvements over the optimised ellipse for this 750 W source in comparison to the 1000 W source for two reasons: (a) the filament of the 750 W source is smaller and therefore more closely resembles a point source and (b) the outlet of the ellipse is much larger, so the difference between the exit plane and the target plane is smaller. This is a major issue associated with the uses of ellipses as described previously in section 6.2.

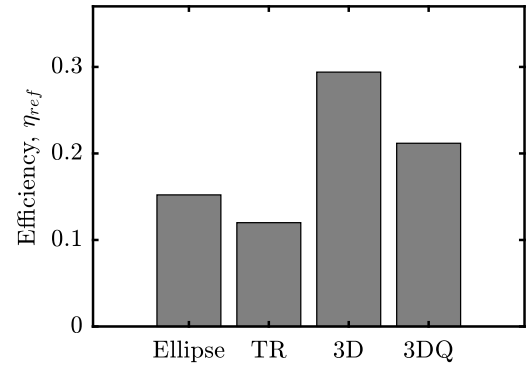
It is noted that the surface preparation for the two reflectors is not directly comparable — the reflector surface of the PCS unit was not finished to a highly specular state as-received. Therefore, the difference between these two units may be reduced if a similar surface finish is applied to both reflectors. However, given that the custom shape shows higher efficiency than the optimised ellipse, it has been demonstrated that the design process delivers substantial improvements over the conventional spheroidal shape when using this source.

8.3.2 3000 W source

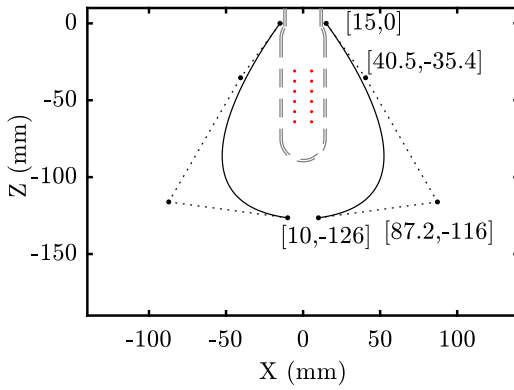
The 3000 W lamp can also be used as the seed source for a custom reflector and compared to the GL398 commercial device manufactured by Thermo Riko. The 3000 W lamp is considerably larger than those investigated so far in this work. The length of the lamp housed within the reflector is over 90 mm, as shown in Fig. 8.6c, which implies the limit on the minimum reflector length is ~ 120 mm. The measured dimensions and a schematic of the lamp are provided in Appendix C.1. This lamp includes two primary supports which have been modelled as three separate bodies. As with the 1000 W lamp, the curved element of the support (located at ~ 75 mm on the z-axis) is neglected due to the additional complexity of modelling this aspect and the insignificant improvements this would provide to the accuracy of the simulation. The filament is characterised by six turns of a 2 mm diameter coiled-coil, which has been modelled as a series of tori of the same diameter. The quartz envelope does not form into a solid base in the area of interest to this study, but instead tapers slightly from 30 mm to 25 mm diameter and then extends another 40 mm to the ceramic base. The lamp is set to pass through the upper surface of the reflector in the model at the taper point



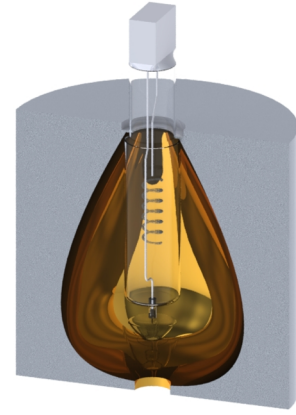
(a) Three iterations of the 3D optimisation process for the 3000 W lamp.



(b) Comparison between the optimised Au reflector to that of the TR unit, ellipse, and a quartz guide rod version.



(c) The optimised shape with annotated Bézier curve points.



(d) 3D view of the optimised reflector and QTH.

Figure 8.6: Optimisation of a reflector with the 3000 W source.

to 25 mm diameter. Therefore, this lamp geometry requires a large orifice (26 mm diameter to account for tolerances) where radiation can be lost from the reflector enclosure. This is contrasted to the smaller lamps tested which have 6.5 mm × 19.5 mm and 4.2 mm × 14 mm square orifices for the 1000 W and the 750 W lamp respectively. With the 3000 W lamp, one would expect disproportionately higher losses from the entrance of the reflector due to the area being 4-8 times larger area than the other lamps with only 3-4 times the power output.

The optimisation results for the 3000 W lamp are shown in Fig. 8.6 with a peak efficiency value of 29.4% when recalculated with 250k rays. There is a noticeable difference between the sizes of the three shapes, as shown in Fig. 8.6a; however, the efficiency converges adequately. Despite the much larger lamp, the optimised reflector is only ~140 mm in length. The Au-coated device is predicted to deliver over 2x the efficiency of the unit supplied by Thermo

Riko with a reflector that is less than half of the size. However, this is not a comparative analysis since the GL398 uses a quartz guide rod which will reduce the intensity at the outlet. A simulation which includes a 150 mm quartz guide rod (approximately equal to the length used by the GL398 device) is also compared in Fig. 8.6b. The quartz guide rod reduced the efficiency to 21% due to the absorption of the quartz bulk and Fresnel reflection losses at the interfaces. Despite this, the optimised device is still predicted to deliver an efficiency which is more than 90% greater than the commercial unit. The Thermo Riko FIRH is already quite efficient in comparison to other commercial FIRHs and the ideal ellipse shape, particularly given that this unit employs a quartz guide rod.

The 3000 W lamp presented here is not ideal for this design strategy. This lamp does not allow one of the main benefits of this technique to be exploited, which is the precise shaping of the reflector entrance to the lamp base to increase the reflective surface area within the enclosure. Since this lamp is so large, it is not practical to fit the reflector around the lamp, as the overall size of the reflector would be markedly increased. Therefore, the efficacy of the optimisation process will be reduced. Despite this drawback, the optimisation technique delivered considerable improvements to the performance of the FIRH using this source in comparison to the commercial unit and the ideal ellipse.

8.4 Selection of a FIRH outlet size

So far in this work, reflectors with a specific outlet requirement or the optimisation of commercially available units have been demonstrated. However, the choice of an outlet size is one which must be considered carefully. In some cases, a FIRH may be specifically designed for an application which will fix the outlet size (e.g. heat treatment of a component of a given width, or welding of polymer joints), but in others, the FIRH may be designed with a specific performance metric in mind. The three generalised objectives that may be designed for during the development of a FIRH are as follows:

- (a) The most forthright objective is to maximise the efficiency of the radiation transfer from the source to the target.
- (b) Secondly, a designer may wish to maximise the heat flux on the target surface for applications where high intensity is necessary.
- (c) As observed throughout this work, the maximisation of (a) or (b) will often be achieved

to the detriment of the other. Therefore, the final design strategy is to strike a balance between (a) and (b) such that both are optimised concurrently.

The design of a reflector for the first objective is well understood and has been covered extensively in the literature. Optimising for efficiency can be achieved by matching the étendue of the target to that of the source such that all radiation can be transferred without significant losses. The effect of the differences in skewness distribution between the source and the target can also be considered if necessary.

However, the design of a FIRH for high heat flux applications or a combination of high heat flux and efficiency has yet to be detailed. The most probable reason for this is that designing for a heat flux based objective is more involved and requires taking into account the power output of the source as well as the efficiency of the transfer process. As demonstrated in section 6.6.5, the power output from a source located within a FIRH depends on the rate of light recycling, which is a function of the geometry of the filament, shape of the reflector, and the reflectivity of the enclosure. Modifying the outlet area affects the rate of light recycling and hence, the power emitted from the lamp. Analysing this effect and establishing design guidelines for the outlet size of a FIRH which accounts for the trade-off between heat flux and efficiency is the primary goal of this section of the work.

For the remainder of this chapter, a single source will be chosen to simplify the analysis. Due to the large size and unfavourable reflector entrance characteristics of the 3000 W lamp, it will not be studied further. The radiance of the source can be used to choose between the 750 W and 1000 W lamp since a higher radiance will translate to higher maximum performance from the FIRH. The 750 W source and the 1000 W source have étendue values of 1160 and 1800 mm²sr respectively. When the power output is divided by the étendue, the radiance of the sources can be determined to be 650 and 560 mW/mm²sr, respectively. Therefore, the 750 W lamp delivers 15% higher radiance and will be utilised going forward.

8.4.1 Simplified outlet specification strategy

To develop an outlet specification method, the problem will first be analysed using NIO theory while assuming that the effect of light recycling is negligible. Although light recycling is important to the overall performance, a simplified model will still aid the understanding of the effect of outlet size on the performance of a FIRH and establish theoretical design guidelines. The skewness distributions between the source (21 mm $\times$ 5.8 mm cylindrical source) and the target can be analysed using the methods outlined by *Ries et al.* [94]. An example schematic with a 10 mm radius target disk and the 750 W source is shown in Fig.8.7, which illustrates the main aspects of skewness losses (red) and dilution of the radiation (blue) on the target surface. The radiation that can be transferred from the source to the target is illustrated by the overlap between the two distributions which is shown in green on the diagrams. Both losses and dilution are attributed to differences in size and shape of the phase space of the source and target. The losses manifest as a limit on the permissible transfer efficiency, and any resulting dilution causes a reduction of the radiation intensity on the target surface. An analogy is “fitting a square peg into a round hole”: even though the square peg might have a smaller area (étendue) than the round hole, it may not fit due to the shape difference. The rotational skewness limit may be overcome by using a

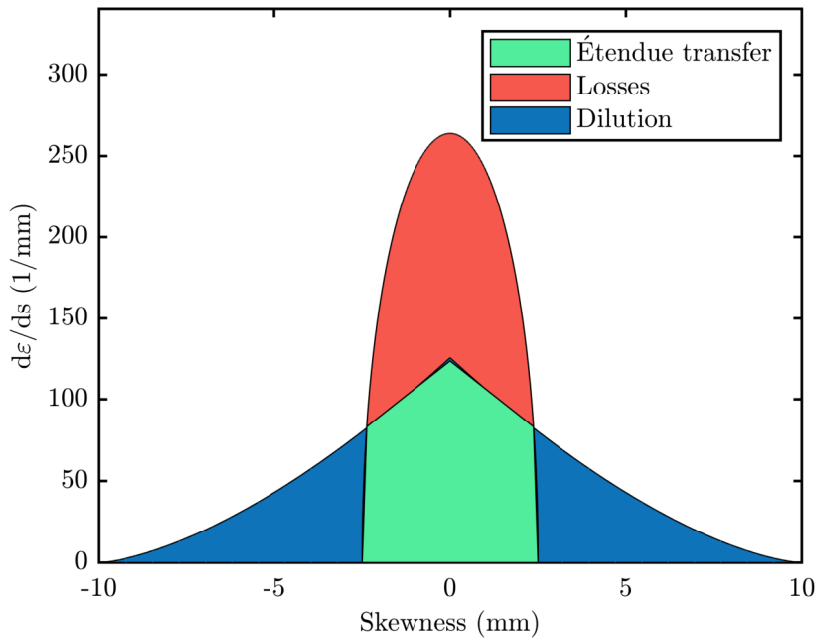
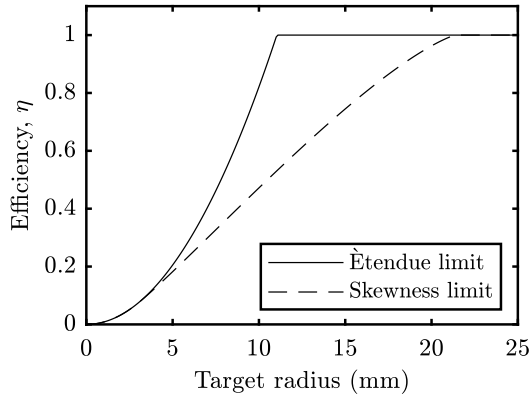


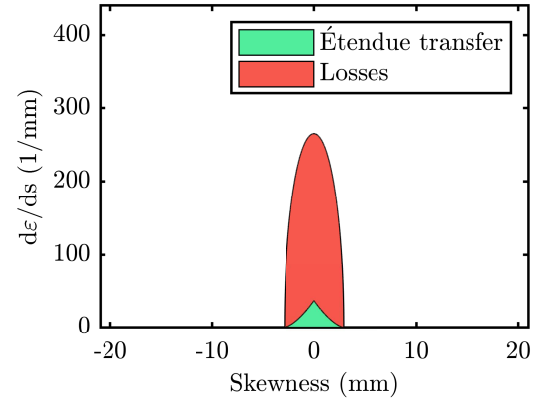
Figure 8.7: Schematic of skewness losses and dilution for a 5.8 mm $\times$ 21 mm cylindrical source and a 10 mm target disk. The green area is the only fraction of the sources étendue which can be received by the target, and represents 47% of the sources étendue.

nonrotationally symmetric reflector, such as those proposed by *Shatz et al.* [175] or light recycling [47].

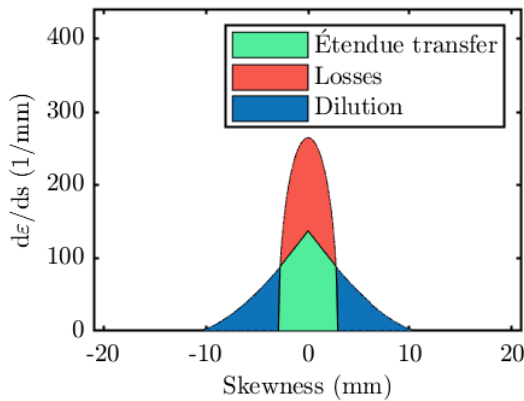
Fig. 8.8 shows how the étendue and skewness limits change with the target radius and how the asymmetry of the cylinder source limits the transfer efficiency. Fig. 8.8b-d shows the skewness distribution for three representative outlet diameters, which correspond to a dilution-optimised outlet at a radius of 2.9 mm, an étendue-optimised outlet at a radius of 10.9 mm, and a skewness-optimised outlet at a radius of 21 mm. These are compared to the phase space of the 2.9 mm radius $\times$ 21 mm height 750 W cylinder source. It is noteworthy that in Fig. 8.8b there is no dilution occurring (i.e. no blue region) and it is not until 21 mm radius that the theoretical losses have entirely been eliminated as shown in Fig. 8.8d. In between these two radii, losses and dilution both play a role in driving the performance of



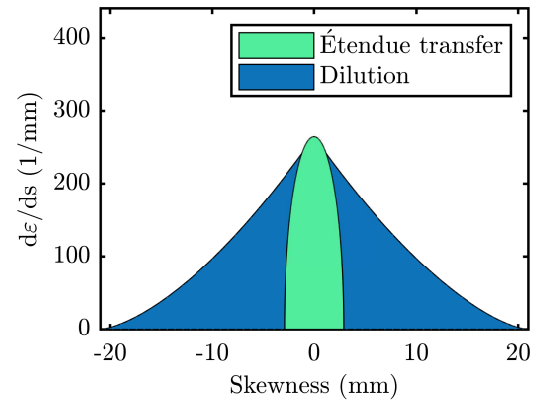
(a) Étendue and skewness limits for various target disk sizes.



(b) The skewness distribution of a cylindrical source and disks of 2.9 mm.



(c) The skewness distribution of a cylindrical source and disks of 10.9 mm.



(d) The skewness distribution of a cylindrical source and disks of 21 mm.

Figure 8.8: Analysis of a 2.9 mm radius $\times$ 21 mm height cylindrical source with various disk target sizes.

the radiation transfer process.

The radius corresponding to the étendue limit can be calculated by equating the étendue of the source (1160 mm²sr) to the target (see Eq. 2.23 and 2.24 on page 49) and rearranging:

$$r_{\dot{E}} = \sqrt{\frac{1160^2}{\pi}} = 10.9 \text{ mm} \quad (8.1)$$

This assumes that the theoretical maximum outlet angle of 90° is possible. The skewness limit is not as trivial to solve for a general case, but the details of the necessary equations to do so can be found in reference [94]. However, one can observe that for the case of a cylinder source, the skewness limit is reached when the outlet radius is set to the height of the cylinder.

The concept of a dilution-optimised reflector has not been discussed in the literature so will be briefly outlined. When the radius of the target is below that of the source, an increase in the radius of the target results in a proportional increase in the radiation that can be transferred from the source to the target based on the principles of étendue and skewness. As the target radius is increased to greater than that of the radius of the cylinder source, a skewness difference between the source and target will manifest and begin to limit the transfer efficiency. This results in a reduction of the heat flux intensity as the proportion of radiation that can be received by the target from the cylinder source (defined by skewness) grows more slowly than the total radiation that can be received by the target under optimal conditions (defined by étendue). This is illustrated by the divergence of the étendue and skewness limit starting from ~3 mm in Fig. 8.8a, whereas less than this target radius, the étendue and skewness limits increase at the same rate and are equivalent.

To determine the effect of outlet size on the efficiency and heat flux in this simplified model, one can assume that the FIRH transfers radiation from the source at the theoretical skewness limit. The heat flux output of the device can then be calculated based on this assumption and that the power input to the lamp is a constant value of 750 W:

$$\bar{q}'' = \frac{\eta_{skew} \times P_{750 \text{ W}}}{\pi r_{target}^2} \quad (8.2)$$

The effect of changing the outlet radius on the efficiency and heat flux output of the device can then be plotted, as shown in Fig. 8.9. Four zones can be observed, which are separated by the dilution, étendue, and skewness limits. The first zone (I) is the zone of high heat flux

which extends from a radius of zero to the dilution limit located at 2.9 mm. In this region, the heat flux level is flat due to the efficiency of the transfer process being only a function of the étendue limit, which scales at the same rate as the target area.

The second zone (II) is the low efficiency zone and is characterised by a rapid drop in the heat flux on the target surface, which is attributed to the dilution of the radiation output as the radius of the target exceeds that of the cylinder source. The efficiency increases in this region due to the enlargement of the target area; however, the rate at which the efficiency increases is less than that of the area, resulting in a reduction in heat flux. This zone extends to the étendue limit at 10.9 mm, where the high efficiency zone begins (III). At the boundary of the high efficiency zone, there is no evident change in the rate at which the heat flux decreases; however, the crossover into this zone is marked by the fact that the target now has sufficient étendue to receive the entire output of the source, but the efficiency of doing so is limited by skewness differences. This zone will decrease in size if the skewness difference between the source and target is reduced and will be completely negated if the source and target skewness distributions are matched. In the case of matched skewness distributions of the target and source (i.e. étendue and skewness limits are equivalent over the range target radii of interest), only three zones will exist on this schematic.

The final zone is the low heat flux zone where the efficiency will saturate, and the heat flux will continue to taper off due to the growing target area at a constant power output. It is noteworthy that the heat flux drops at a marginally higher rate in this zone because increasing the size of the target only causes further dilution. Thus no benefit can be derived from increasing the outlet size from either a heat flux or efficiency standpoint. The crossover point of the efficiency and heat flux occurs at the étendue limit for this particular source geometry. However, this has no physical significance and is simply a function of the scaling of the axis (which are both scaled to 1.1 times the max value) and the étendue and skewness limit ratios. For example, increasing the length of the cylinder source increases the skewness and shifts the crossover point to higher radii.

This schematic and model provides a great deal of insight into how to select an outlet size for a given application, and hence, this technique can be used as a general guide when designing a FIRH. For example, for applications that require the highest heat flux outputs (such as metal annealing and testing of high-temperature components), the high heat flux zone is an appropriate area to specify the outlet size. It would be prudent to choose the outlet size at approximately the dilution limit as this maximises the heat flux while maintaining the

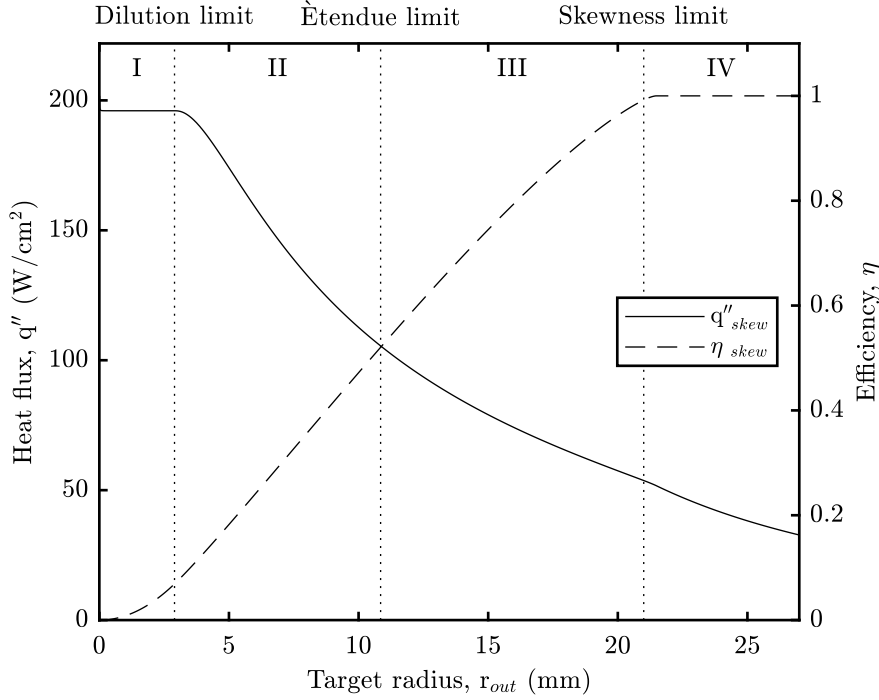


Figure 8.9: The effect of outlet radius on the heat flux and efficiency of a FIRH with a 5.8×21 mm cylinder source derived from the skewness limit. The four zones labelled are: (I) the high heat flux zone, (II) low efficiency zone, (III) high efficiency zone, (IV) low heat flux zone.

highest efficiency possible for this heat flux level. A slightly larger radius than the dilution limit can be chosen since the étendue at the outer edges of the disk is so small that only a minor decrease in heat flux is observed but a disproportionate benefit in terms of higher efficiency is delivered.

Several applications may be suited to the low and high efficiency zone such as paper drying, food processing, and thermoforming depending on the specific efficiency and heat flux needs of the application. The low heat flux zone may be suitable for space heating, low-temperature curing or similar applications. This area is outside of the remit of this work and therefore will not be discussed further. For applications with a specified outlet size requirement, the outlet can be fixed, and the lamp selected such that the appropriate source to target size ratio is achieved. Despite the development of techniques which can negate the effect of the rotational skewness limit, effort should be made to procure lamps that do not have a large symmetry discrepancy so as to maximise the efficiency of the FIRH.

The heat flux and efficiency can be optimised simultaneously by maximising the product of these two variables and assuming an equal weighting for both. This product may be conceptualised as a *heat flux utilisation factor* (HFUF) which represents how efficiently a

given heat flux is delivered by the FIRH. The units of this metric will be shown as W^2/Wcm^2 to distinguish from a standard heat flux. A plot of this product is shown in Fig. 8.10 across the same range of outlet areas as considered previously. The HFUF is maximised at an outlet radius of 15 mm with a value of $\sim 60 W^2/Wcm^2$ in the high heat flux zone. This corresponds to a heat flux of $78 W/cm^2$ and an efficiency of 74%. This figure also suggests that operating anywhere in the high efficiency zone is reasonable for the HFUF with only a small difference between the maximum and minimum value within this range. Conversely, selecting an outlet that falls within the low efficiency or low heat flux zone leads to a sharp drop in the utilisation factor.

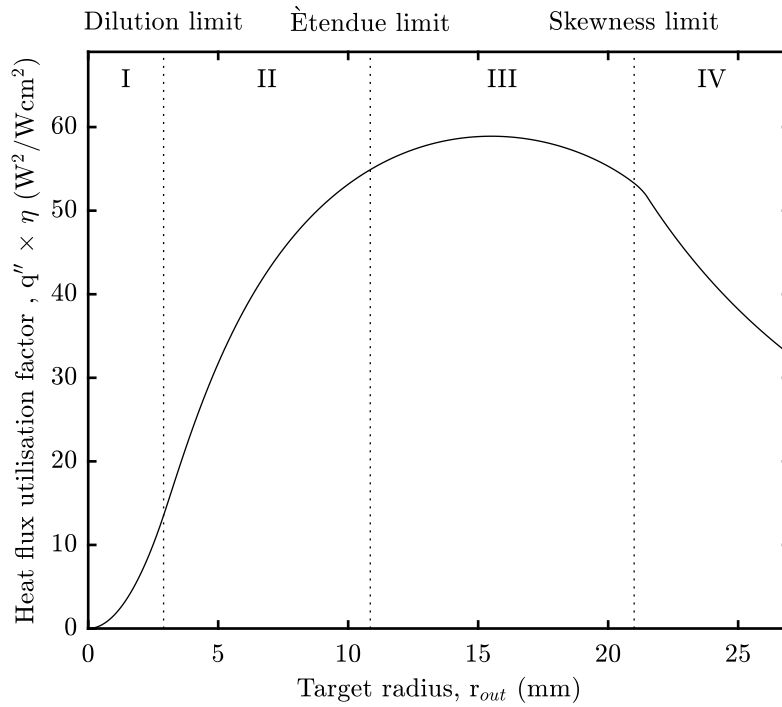


Figure 8.10: The effect of outlet radius on the product of the heat flux and efficiency of a FIRH with a 5.8 mm $\times$ 21 mm cylinder source derived from the skewness limit.

The simplified model developed requires several assumptions. Firstly, the power output of the lamp is assumed constant and does not change depending on the reflector geometry and confinement level. It was shown in Chapter 6 that the power output of the lamp is a function of the rate of light recycling, which in turn is dependent on the outlet area of the reflector. Secondly, it is assumed that the efficiency of the reflector is given by the skewness limit. Although a reasonable estimate, this completely neglects the specifics of the actual reflector. Further, it has been shown that this limit can be overcome through the process of light recycling [47] or asymmetric reflector shapes [175] and thus, this is not a hard “limit”.

Analysis of the rate of light recycling experienced by the source within the enclosed reflector is required to allow the inclusion of these effects in a more comprehensive model.

8.4.2 The effect of light recycling

Aside from the simplified model provided in section 8.4.1, the reflectors developed have been analysed and compared in terms of efficiency while using the model. Metrics such as heat flux or power output have not been considered due to the uncertainty surrounding the power output of the lamp. The more enclosed the lamp is (i.e. the smaller the outlet relative to the source), the more often the reflector will tend to direct radiation back to the source, and the less power that will be dissipated from the filament, assuming a constant temperature is maintained. Hence, the rate of light recycling is fundamental to the overall radiative performance of the source and reflector combination.

As described in section 6.6.5, there are three thermal performance conditions which need to be considered:

1. The thermal performance of the lamp if there was no light recycling occurring i.e. the emitting surface is convex.
2. The “base” thermal performance of the lamp in the as-received state.
3. The thermal performance of the lamp when enclosed within the reflector.

Each of these conditions will be referred to as the “convex”, “base”, and “reflector” states with associated subscripts of C , B , and R , respectively. The recycling rate in the convex state is by definition zero, but of interest to this study is the power emitted from a convex filament, P_C , as this allows calculation of the radiative power output from the filament while enclosed within the reflector. Hence, this value is necessary to determine the heat flux and radiative power output of the FIRHs developed using the 3D model.

The rate of light recycling can be calculated via RT by assuming a fully absorbent filament and then dividing the number of rays absorbed by the total number of rays emitted from the filament surface [47]:

$$\xi = \frac{N_{abs}}{N_{tot}} \quad (8.3)$$

Since the coiled-coil filament needs to be taken into account, the 3D ray tracing algorithm model developed in Chapter 7 cannot be used. Therefore, a custom algorithm was developed

which allows the complex filament structure to be traced in its entirety. For clarity of this section of the work, the details of this algorithm are not included here but can be found in Appendix C.3.1. The 750 W coiled-coil filament was simulated and found to have a recycling factor of $\xi_B = 0.69$ without any enclosing reflector geometry. This is significantly higher than the recycling rate of between 0.3 and 0.4 that was found by Fu for single coiled filament [47] but of a similar order of the base recycling factor of 0.61 found for the 1000 W lamp in section 6.6.5. The power factor, γ , is a function of the emissivity and recycling factor:

$$\gamma_B = \frac{(1 - \xi_B)}{1 - \xi_B(1 - \varepsilon)} = 0.58 \quad (8.4)$$

The spectrally averaged emissivity is the same value of 0.33 that has been used throughout this work. The convex power can be found using the base power factor:

$$P_C = \frac{P_B}{\gamma_B} = 1230 \text{ W} \quad (8.5)$$

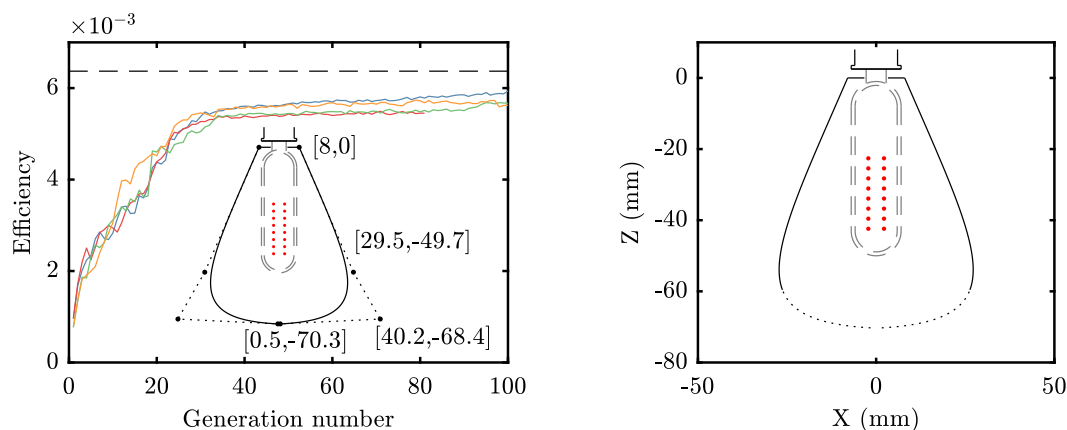
P_B is assumed to be the product of the nominal lamp power input of 750 W and a radiative efficiency of 95% similar to the lamp tested in Chapter 7. The convex power calculated through the power factor can be validated using the Stefan-Boltzmann law to determine the power output from a convex body:

$$P_C = \varepsilon A_s \sigma (T_s^4 - T_\infty^4) = 1110 \text{ W} \quad (8.6)$$

A_s is the filament surface area which was determined to be $7.3 \times 10^{-4} \text{ m}^2$ using the methods outlined in section 3.2.3. This value agrees reasonably well with the power calculated through the light recycling factor. The difference between these values may be attributed to several causes, including the uncertainty associated with the area of the filament, the geometry of the filament and the radiative efficiency used to calculate the nominal radiative power. The base light recycling factor can also be used to determine the effective emissivity of the filament:

$$\varepsilon_B = \frac{\varepsilon}{1 - \xi(1 - \varepsilon)} = 0.61 \quad (8.7)$$

The effective emissivity of the lamp is $\sim 85\%$ greater than would be expected from a convex tungsten source. This highlights the benefits of the coiled-coiled geometry not only in terms of reducing convective losses (as described in section 2.3.2 and reference [28]) but also in



(a) Mean efficiency value during the optimisation for the 1 mm outlet diameter optimised reflector. (b) The variable outlet size of the reflector marked (from 1 mm to 42 mm diameter) by a dotted line.

Figure 8.11: Optimisation of the 1 mm outlet diameter.

terms of enhancing the effective heat flux output from the lamp.

A reflector was optimised for a 1 mm outlet (which can be considered the smallest practical outlet size for the 750 W lamp) to analyse the effect of light recycling on the performance of the FIRH. The resulting shape from this optimisation is shown in Fig. 8.11a. This reflector is particularly challenging to optimise since the outlet size allows so few rays to exit the reflector. This leads to an increase in the statistical variance of the process, which was $>30\%$ for 10k rays. Therefore, to reduce the variance, 100k rays were employed, with an expected statistical error of $<10\%$. The predicted efficiency of this shape is only 0.6%, and thus, only 2-3 W will be emitted from the exit. The outlet of this optimised device can then be increased to match the range of outlet sizes analysed in section 8.4.1 by truncating the bottom of the reflector, as shown in Fig. 8.11b with dashed lines. This allows a range of outlet sizes to be tested without modifying the overall reflector shape which would not be possible if a larger outlet size was scaled down without using error-prone extrapolation.

Fig. 8.12a shows the recycling factor plotted against the skewness limit of the reflector for the various outlet sizes tested. The base light recycling factor is also shown as a horizontal dashed line at 0.69. There is a correlation evident between the light recycling factor and the skewness limit for this reflector. The 1 mm diameter exit results in the maximum recycling factor of 0.88. The minimum recycling factor of 0.76 results when the outlet is enlarged to 42 mm diameter, which corresponds to the skewness limit. The effective emissivity and power factor are also provided in Fig. 8.12b. The trade-off between power output and effective emissivity is evident in this figure with the effective emissivity rising and the power output

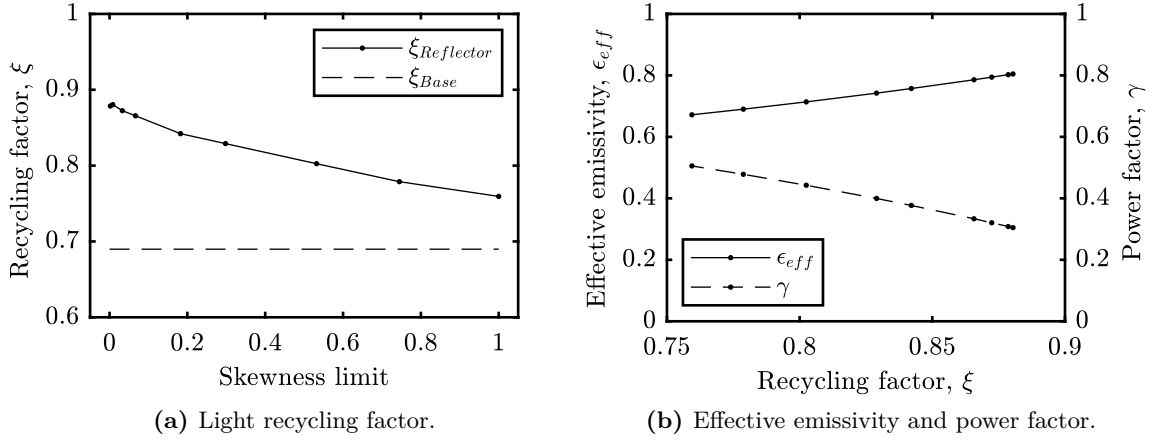


Figure 8.12: The effect of skewness limit and recycling factor on emissivity and power factor.

reducing with an increase in the light recycling factor. The effective emissivity ranges from between 0.68 and 0.8, which equates to an 18% increase in radiance from the least confined reflector to the most. Compared to the material emissivity of tungsten, the process of light recycling is predicted to cause an increase of 140% compared to the initial value of 0.33. Conversely, the power factor decreases from 0.49 to 0.30 for the least to the most confined state. Although lower power output is not beneficial for the overall thermal performance of the lamp, the exchange for higher source radiance is advantageous, which permits higher heat flux outputs from a FIRH.

8.4.3 Generalised outlet specification strategy

Now that the light recycling factor and power factor have been found, a more comprehensive model can be constructed to allow the specification of an outlet size. The same method described at the beginning of section 8.4.1 will be employed where the calculated reflector efficiency is used to determine the heat flux output, but now also taking into light recycling and the power factor. The efficiency is found using the 3D MCRT model, and the power output of the source is adjusted by the power factor for a given skewness limit (see Fig. 8.12):

$$q'' = \frac{\eta_{RT} \times P_{rad} \times \gamma}{\pi r_{target}^2} \quad (8.8)$$

As illustrated in Fig. 8.13, a similar trend is depicted when compared to the simplified model. However, there are several differences.

Firstly, the saturation of the heat flux output in zone I is not evident. This can be

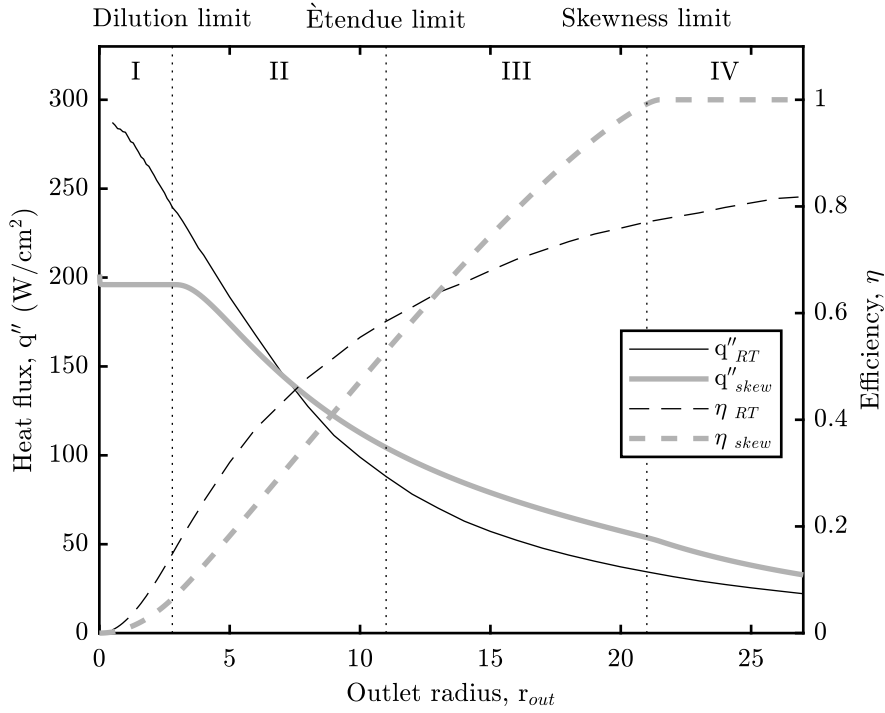


Figure 8.13: The effect of outlet radius on the heat flux and efficiency of a FIRH with a 5.8 mm × 21 mm cylinder source based on the 3D MCRT model. The four zones labelled are: (I) the high heat flux zone, (II) low efficiency zone, (III) high efficiency zone, (IV) low heat flux zone. The NIO optics curve for heat flux and efficiency are also included.

attributed to the increased rate of light recycling under more confined reflector conditions, which allows the heat flux output to increase monotonically as the outlet is reduced in diameter. Based on the saturation of the heat flux in this zone for the simplified model, the dilution limit was proposed as an optimal design point for high heat flux applications. Fig. 8.13 suggests that for a more realistic model, this trend does not occur. However, this limit is still considered to be a suitable design guideline for high heat flux output designated FIRHs. The reasoning for this is due to the marginal increase in heat flux output (260 W/cm² vs 300 W/cm²) versus the more sizeable decrease in efficiency (17% vs 0.6%) when comparing the dilution-optimised reflector to the 1 mm diameter outlet FIRH. Therefore, given the rate of the reduction in heat flux as the radius is increased past the dilution limit, and that there is no significant benefit derived from employing a smaller outlet, the use of the dilution limit as a design point for high heat flux applications is suggested. It is noteworthy that the heat flux level predicted using the MCRT model of ~300 W/cm² is considerably higher than the analysis based on the NIO theory limit allows. This can be linked to the fact that the effective radiance of the source has been increased by a factor of almost 2.5, and thus for an unbiased comparison, the skewness limit also must be adjusted by this factor.

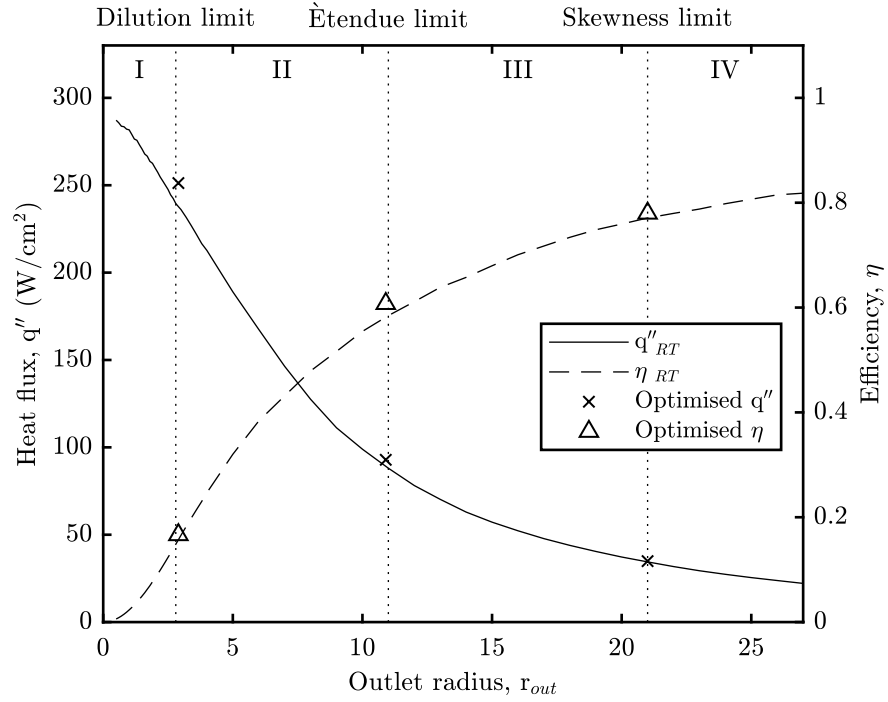


Figure 8.14: Comparison between the variable outlet and the optimised shapes.

Similar trends are observed in the high and low efficiency zones when compared to NIO theory with the efficiency increasing but not at a high enough rate to maintain a constant radiation intensity. The efficiency asymptotically increases in the low heat flux zone in this model and does not reach the maximum value at the skewness limit, which can be explained by the fact that losses from imperfect interactions are taken into account with the reflector wall and quartz envelope. As the outlet area is increased further, the likelihood of the radiation exiting without interacting with an absorbing surface is improved and hence the efficiency increases slowly. This effect was also observed by Brennesholtz [91] for a light projector system as the étendue of the outlet aperture was increased past the étendue limit for the source tested.

The modelling technique of adjusting the outlet size of an optimised reflector for a 1 mm diameter outlet allows this trend to be analysed - it is not feasible to optimise a reflector for each of the design outlets of interest while maintaining a reasonable MC simulation statistical error. However, a reflector shape optimised for a 1 mm outlet diameter is not ideal for testing with a 42 mm diameter outlet. Therefore, reflector shapes were optimised at each of the dilution, étendue, and skewness limits and are plotted in Fig. 8.14 as additional data points. The data points align well with the overall trend, although delivering slightly

higher efficiency and heat flux in all cases as expected since the shapes are optimised for that particular outlet size. Each of the shapes developed by the GA for these particular outlet sizes are quite similar in comparison to the optimised shape for the 1 mm outlet, as shown in Fig. 8.15; although the differences do lead to efficiency improvement of between $\sim 5\text{-}10\%$. The fact that the 1 mm diameter outlet performs quite well across the entire range of outlet sizes tested may indicate that the upper portion of the shape of the reflector near the lamp plays a more prevalent role in determining the performance of the FIRH when compared to the portion near the exit.

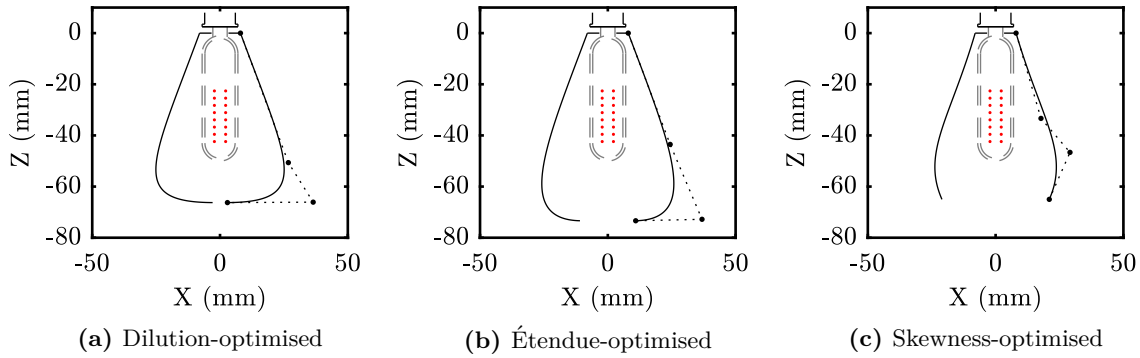


Figure 8.15: Optimised reflectors for various outlet sizes.

The HFUF can also be determined based on the more comprehensive outlet specification approach. A comparison between the HFUF for the RT and NIO techniques is presented in Fig. 8.16. For the more realistic RT model, the curve is shifted to the left due to the effect of light recycling increasing the efficiency and heat flux output of the FIRH. There is also a much narrower peak at ~ 6 mm outlet radius, which is contrasted against the broader NIO profile for which the maximum is found at ~ 15 mm. At this design point, the efficiency is predicted to be 34% with a heat flux of 165 W/cm^2 , which provides a balance between high heat flux and high efficiency and falls within the low efficiency zone.

To summarise, three methods have been described for determining the outlet size of a FIRH based on the application requirement:

1. The skewness limit can be used to specify FIRH outlets for applications where high efficiency is desired.
2. The dilution limit can be used where high heat fluxes are necessary.
3. A balance between these two metrics can be achieved by maximising the product of

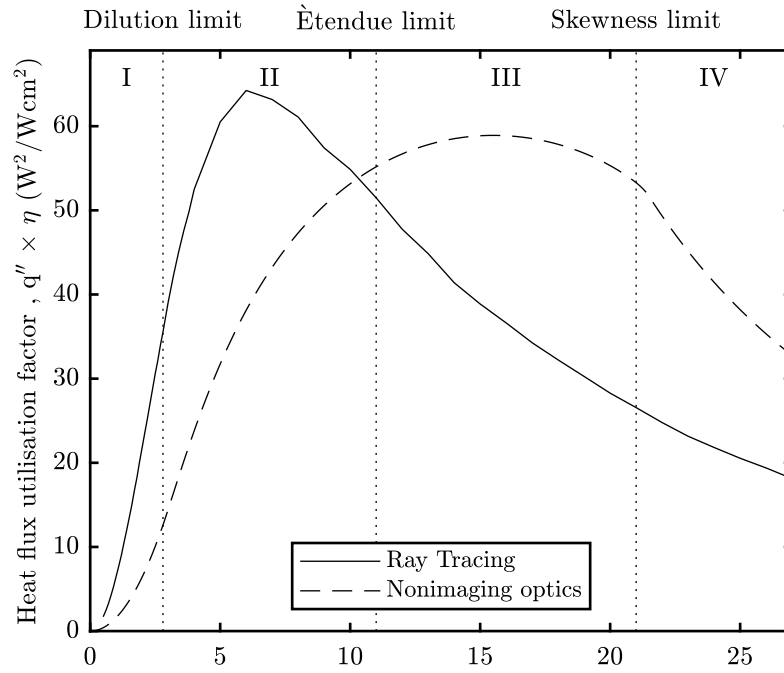


Figure 8.16: The effect of outlet radius on the heat flux utilisation factor.

the efficiency and heat flux which will place the reflector design in the low efficiency or high efficiency zone.

The simplified model tends to underpredict the performance of the FIRH in the low heat flux zone and overpredict in the high heat flux zone, but overall, the trend tends to agree with the more comprehensive model. Therefore, the design procedure of mapping the efficiency and heat flux output by assuming a constant efficiency metric (i.e. skewness limit) is deemed to provide a suitable outlet specification strategy for the initial design of a FIRH. It must be taken into account that this design strategy will likely predict larger outlet size than desired in the high heat flux and low efficiency zone since light recycling is neglected. If more accurate predictions are necessary, the techniques outlined which involve determining the efficiency and light recycling factor through RT may be used as a part of an iterative design strategy.

8.5 Nondimensionalised metrics

The final issue that arose during this investigation which needs to be considered is that it is challenging to directly compare the efficiency of reflectors with different source and outlet sizes. This limited the ability to compare the performance of reflectors developed in the early

stages of this work to that of the commercial FIRHs. A metric which can describe how well a reflector performs irrespective of the source size and outlet geometry is therefore necessary.

The étendue limit defines the maximum efficiency at which radiation can be transferred from a source to a target based on their respective geometries. A more representative comparison between FIRHs can be made if the efficiency is normalised by the étendue efficiency for a given source and target:

$$\eta_{norm, \dot{E}} = \frac{\eta_{FIRH}}{\eta_{\dot{E}}} \quad (8.9)$$

However, the étendue limit does not take into account differences in the skewness between source and target. For a reflector that employs an asymmetric source, the skewness limit should instead be used to normalise the FIRH efficiency:

$$\eta_{norm, skew} = \frac{\eta_{FIRH}}{\eta_{skew}} \quad (8.10)$$

Both the étendue and skewness normalised efficiency have a physical meaning: if unity is surpassed for either of these metrics, the respective transfer limits have been exceeded for a convex source.

Table 8.1 shows a comparison between the optimised reflectors for the 750 W, 1000 W, and 3000 W lamp. One would expect that each of these reflectors would deliver similar performance when evaluated using a suitable metric since they are “optimised”. As shown, the efficiency of the reflectors varies significantly with the highest value being 90% greater than the lowest. The difference between the reflector performance is reduced when taking into account the transfer limit of the source and target based on étendue. Interestingly, the 750 W source now performs the worst of the three reflectors. This can be attributed to the large outlet relative to the size of the source and the significant dilution that results. In contrast, lower levels of dilution occur for the 1000 W and 3000 W reflectors, and therefore these sources deliver improved performance according to this metric.

When the reflector efficiency is normalised by the skewness efficiency, a more comparable performance is observed with only a 17% difference between the best and worst efficiency levels. The discrepancy may be accounted for by other aspects of the FIRH which cannot be incorporated into these metrics such as the size and position of the supports, the geometry of the quartz, and the reflector inlet size. Furthermore, these metrics assume that the comparison is made between reflectors of a similar type, i.e. comparing a reflector from the low heat flux zone to that of a reflector in the high heat flux zone will not yield a useful

comparison.

To take an example from earlier in this work, one could compare the $\eta_{norm, skew}$ of the 2D optimised 1000 W unit to the PCS 750 W unit and the Thermo Riko GL398 3000 W unit. The $\eta_{norm, skew}$ of these devices are 1.52, 0.41, and 0.62 respectively. It is quite clear that the optimised reflector is superior. The concept that this optimisation process delivers improved performance was borne out in the analysis at the beginning of this chapter where a shape was optimised for each of these sources; however, the metric posed, if developed at the time, would have provided a strong indication that the FIRHs developed was a substantial improvement over the commercial reflectors.

Taking account of the differing light recycling rates for each of the reflectors would provide an improved metric. However, developing a metric which can accurately account for the nonlinear behaviour of light recycling proved challenging. Despite this, the metrics described provide a more representative evaluation of the performance of a FIRH reflector and allow the broad comparison of reflectors with differing source and outlet sizes.

Table 8.1: Metrics for comparing reflectors of different source and target geometries.

FIRH	η_{FIRH}	$\eta_{norm, \acute{E}}$	$\eta_{norm, skew}$
GA optimised 750 W	0.46	1.13	1.53
GA optimised 1000 W	0.23	1.70	1.79
GA optimised 3000 W	0.29	1.34	1.52

8.6 Theoretical maximums

The performance of the FIRHs developed in this chapter for the 750 W source is compared to the theoretical maximum of focused IR technology in Fig.8.17. The thermodynamic limits are considered in Fig.8.17a while the NIO limit of skewness is compared in Fig.8.17b. The maximum heat flux emission from a convex tungsten source and that of a filament within a confined FIRH are also shown as q''_{tung} and as q''_{FIRH} respectively. The heat flux output of the FIRH is said to be limited by the emissivity of the tungsten and temperature of the filament as per the brightness theorem [176]. Based on the results from the 1 mm outlet diameter FIRH, the effective emissivity of the tungsten can be enhanced up to $2.4\times$ the emissivity of the material, increasing the permissible heat flux from a tungsten source and allowing the brightness theorem to be surpassed, similar to what was shown in previous

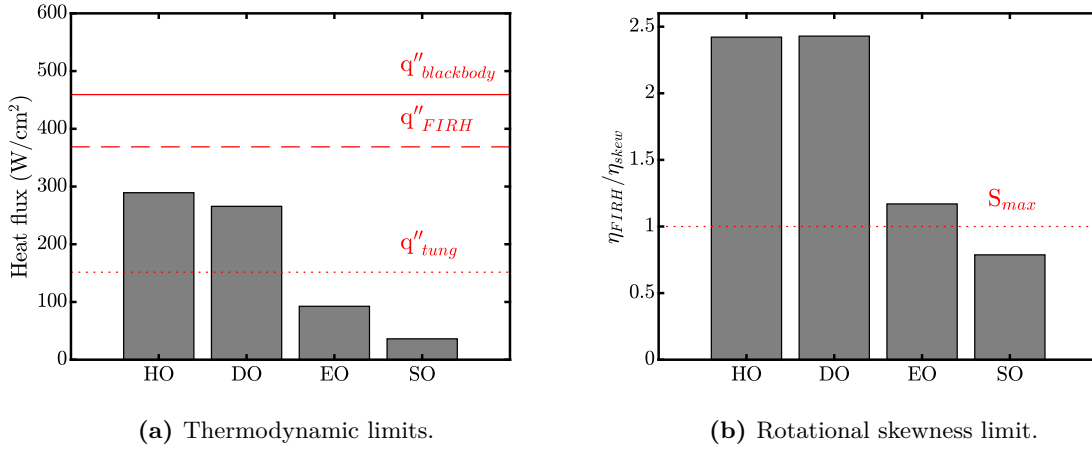


Figure 8.17: Comparison of the theoretical maximum for a range of reflectors at 3000 K source temperature. HO, DO, EO, and SO refer to the heat flux optimised, dilution-optimised, étendue-optimised, and skewness-optimised devices respectively.

research [176]. This is considered to be close to the limit of the heat flux obtainable from a FIRH with useful power outputs and is shown as q''_{FIRH} . The two devices developed that fall within the high heat flux zone of Fig. 8.14 are predicted to exceed the brightness theorem delivering a heat flux of 260 and 300 W/cm^2 and approach the limit set by the effective emissivity. The étendue and skewness-optimised devices have large exits and lower light recycling rates, and therefore provide lower heat fluxes in comparison to theoretical limits. Fig. 8.17b shows the comparison of the various reflectors discussed in this chapter compared to the skewness limit for a convex source. The efficiency of the devices are normalised to the skewness efficiency as per Eq. 8.10, and thus devices which surpass unity can be said to be exceeding the theoretical skewness limit for a convex source. It is noteworthy that this metric shows comparable performance between the HO and DO reflectors despite the difference in outlet size and light recycling rates. Since the reflectors optimised at both the étendue and skewness limits deliver significantly worse performance than the HO or DO FIRHs, it is clear that this metric must be used judiciously and cannot be used to compare FIRHs with vastly different light recycling rates.

The skewness limit is bettered by all of the reflectors developed except the skewness-optimised device, which has larger exit and lower recycling rates in comparison. As expected, the 1 mm and dilution-optimised reflectors have the highest skewness normalised efficiency ratios due to the small outlet and the high rates of light recycling. Both the reflectors optimised at the étendue and skewness limits deliver lower performance in terms of skewness efficiency while benefiting from the source to target transfer efficiencies of over 60% and 75%

respectively. This is counter-intuitive since one would expect that a reflector optimised at the skewness limit would provide the highest performance in terms of skewness efficiency; however, this can be attributed to the increase in performance associated with the higher rates of light recycling brought by smaller outlet sizes relative to the source.

Furthermore, the dilution-optimised reflector actually performs marginally better than the 1 mm outlet diameter according to this metric, which is unexpected since the light recycling rate is higher for the 1 mm source. This be attributed to the difficulty in optimising a reflector with such a low efficiency using a MCRT and metaheuristic algorithm combination due to the statistical uncertainty associated with the simulation. This can be addressed by employing a larger number of rays to reduce the statistical variance but at the cost of additional computation time. Alternatively, an algorithm such as the Kiefer–Wolfowitz method could be considered, which allows the more effective optimisation of problems with statistical noise [127, 128]. However, it is unclear how this algorithm will fare with a problem of this complexity, given that it is a gradient descent based solver.

Fig. 8.18 shows an updated version of Fig. 6.18 from page 158 with the commercial FIRHS, the manufactured FIRHS, and a selection of the devices developed in this chapter. The primary goal of this research was to develop a methodology allowing FIRHS to be designed that more closely approach the blackbody theoretical maximum. The device optimised for 1 mm outlet can be considered the smallest practical outlet and thus will deliver the highest heat flux. The heat flux is $\sim 65\%$ of a blackbody at the same temperature, which is almost 200% higher than either the Thermo Riko or PCS units. Similarly, the other optimised reflectors for the 1000 W and 750 W unit produced heat fluxes which are multiples of those achieved by commercial FIRHS. In the context of the performance of the devices that were developed when compared to the limit of heat flux and skewness, the primary goal of the research has been achieved.

A further increase in the performance of the FIRHS is possible but given unavoidable losses such as the radiative efficiency of the lamp, reflectivity losses, and bulk absorption losses within the quartz, it is likely that the improvement will be small in comparison to those which have been demonstrated in this work. Higher performing FIRHS may be developed by following the recommendations outlined in Chapter 6, most importantly, a more sophisticated finishing strategy (e.g. a process such as electropolishing), higher-order Bézier curves with improved continuity, and nonrotationally symmetric reflectors [177]. Table 8.2 summarises the reflectors developed in this section with the performance compared to commercial devices

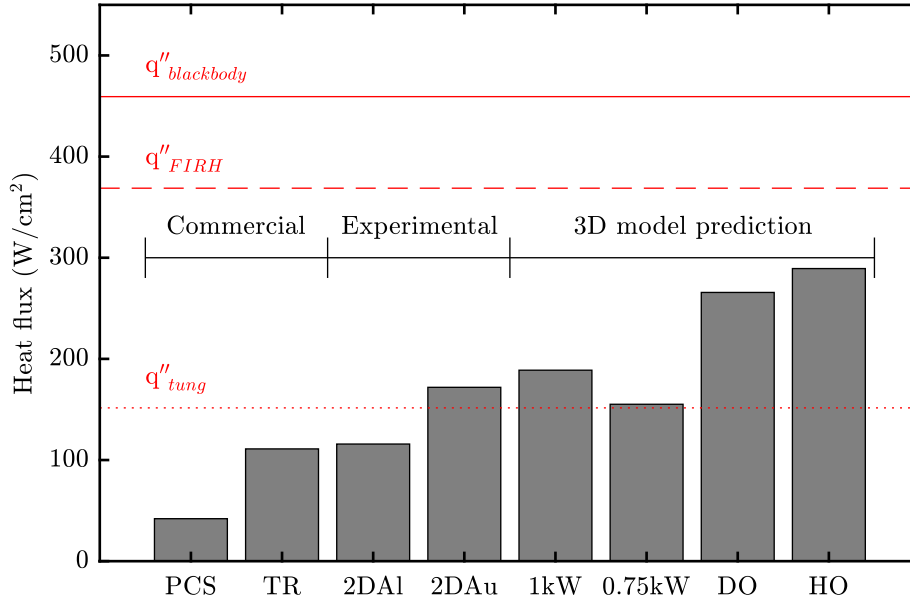


Figure 8.18: Heat flux comparison of the FIRHs developed in this work and those of the commercial units.

as well as to the optimised elliptical counterparts.

There are still, however, improvements to be garnered to the manufacturing process for FIRHs. The SpotIR heater is a low-cost FIRH ($\sim\text{€}2,000$) which compromises on the performance of the device through the economical manufacturing processes employed. Conversely, the Thermo Riko GL 398 device delivers much greater performance than the SpotIR heater, but at a significantly higher cost ($\sim\text{€}20,000$). The total cost of manufacture for the GA optimised FIRH was in the range of $\sim\text{€}2000$ for the Al reflector with an additional $\sim\text{€}1000$ if an Au-coating was necessary. However, this does not take into account the labour time for the manual polishing, which will add a significant fraction to the stated value. The research presented in this thesis will help reduce the overall cost for a FIRH unit of a given performance, but further benefits may accrue with work that is dedicated solely to the manufacture of these devices.

Heating applications that require intensities greater than $\sim 300 \text{ W/cm}^2$ such as the high-speed annealing of metals, welding, or the hard facing of steel, will necessitate radiation sources with higher theoretical heat flux limits. Competing technologies such as lasers and arc lamps are the preferred choice where the capabilities of focused IR are exceeded. However, for the range of applications discussed in the literature review, the high-performing FIRHs developed in this work would be of great benefit.

Of course, the theoretical limits posed in this chapter are based on several assumptions (such as an idealised cylinder emitter for étendue) and uncertainties which are challenging to quantify. Consequently, the limits provided should not be taken as absolute limits, but rather values which provide context to the overall performance of the devices developed in this work or follow on research on this topic.

Table 8.2: Summary of the FIRHS developed in this work and comparison to commercial devices and ideal ellipses.

FIRH	Material	D_{out} (mm)	Adjusted P_{in} (W)	Efficiency	Heat flux (W/cm ²)	Commercial FIRH heat flux (W/cm ²)	Commercial FIRH efficiency	Dimensions (mm) $h \times r$	Ellipse Efficiency	Improvement factor
1000 W (2D)	Au	10	660	19%	161	-	-	87×36	10%	2.0
	Al	10	780	12%	104	-	-	87×36	7%	1.8
1000 W (3D)	Au	10	636	23%	189	-	-	76×34	10%	2.4
	Al	10	729	16%	132	-	-	76×34	7%	2.3
750 W	Au	14	524	46%	155	-	-	69×30	23%	2.0
	Al	14	580	30%	103	42	9%	69×30	18%	1.7
3000 W	Au	20	-	29%	-	111	12%	126×52	15%	2.0
	Al	20	-	20%	-	-	-	126×52	12%	1.7
750 W HF	Au	1	382	0.6%	297	-	-	74×45		
750 W DO	Au	5.8	418	17%	264	-	-	66×26		
						-				
750 W EO	Au	19.2	564	61%	119	-	-	73×25		
						-				
750 W SO	Au	42	636	79%	36	-	-	65×24		
						-				

8.7 Conclusions

The optimisation of a range of FIRHS and strategies for specifying the outlet size of a FIRH have been detailed in this chapter. The following conclusions can be drawn.

It was established that there is a quantifiable difference between the performance of the optimised reflectors developed using quadratic, cubic, and quartic order Bézier curves. The quartic delivered the most efficient reflector shape on average but with a higher level of variance during the optimisation process, which necessitates a larger population size than was practical in this work. This could be addressed in follow on research to deliver further performance improvement to the custom reflectors. Conversely, if computing power is a limiting factor, the use of lower-order curves becomes a viable design choice, as only a minor decrease in performance was observed.

Reflectors were optimised for two alternative QTH sources to allow comparison to the performance delivered by commercially available FIRHS. It was shown that the optimised FIRHS for these sources brought significant improvements versus the commercially available units or optimised ellipses. For the 750 W source within an Al FIRH enclosure, the optimised reflector provided over a 200% improvement in heat flux and efficiency over the commercial unit and 50% greater than an optimised ellipse. The FIRH optimised for the 3000 W source is significantly more efficient with a smaller reflector than the commercially available unit or an optimised ellipse for this source. Hence, this work has established that utilising ellipses for a FIRH reflector is a suboptimal design strategy for nonpoint sources. The reflector shapes developed in this work offer new possibilities and applications for FIRHS due to the capability of these devices to deliver higher heat flux, efficiencies, or a combination thereof, with smaller reflector sizes when compared to conventional elliptical reflectors.

Techniques for selecting the outlet size for FIRHS were proposed. These strategies utilise the geometry of the source to inform an outlet size depending on the heat flux and efficiency requirements of the application. For high heat flux applications and a cylindrical source, it was suggested that an outlet that is approximately the size of the radius of the cylinder should be used. This is referred to as a dilution-optimised reflector which provides a high heat flux with an acceptable efficiency output. A method for determining a balance between heat flux and efficiency was also described such that both metrics were maximised simultaneously.

Finally, the heat flux performance of the FIRHS developed in this chapter was compared to the theoretical maxima for tungsten, a practical FIRH, and a blackbody. The highest

performing device approaches the proposed limit for a practical FIRHs and is and is predicted to deliver over $>65\%$ of the heat flux of a blackbody. Based on this result and unavoidable losses during the radiation exchange process, it is concluded that the limits for focused IR technology are close to being reached. If considerably higher radiant intensities than which have been demonstrated in this work are required, alternative technologies such as arc lamps or lasers should be considered.

Chapter 9

Conclusions and Future work

This work has focused on the development of rigorous optimisation procedure for FIRHs, with an emphasis on improving the thermal performance and reducing the size of these reflectors. This work is concluded by summarising the primary results reported and describing potential follow on research avenues for this topic.

9.1 Conclusions

9.1.1 Characterisation of the QTH lamp

The 1000 W QTH lamp investigated was found to radiate at electrical efficiencies of between 90% and 95% for the power input levels of interest to this study. The radiative efficiency was found to be correlated to the filament temperature, with higher filament temperatures tending to lead to higher efficiencies. Spherical heat flux maps of the source show that the lamp emits an uneven distribution of radiation, which is primarily due to the changing view factor between the sensing element and the emitter surface. A derivation for the filament coil diameter based on accurately measurable or known quantities was provided and employed in the development of the numerical model domain. This derivation proved useful throughout the work, where it was also used to estimate the light recycling factor of the filament.

An axisymmetric numerical model of the QTH lamp was developed and was shown to predict the radiative efficiency of the lamp adequately across the experimental power range tested. This modelling methodology can therefore be employed when investigating the performance of a given QTH lamp or other comparatively sized radiating bodies with semitransparent quartz envelopes. The correlation of efficiency with the temperature of the filament

was further highlighted, with losses of up to 45% predicted at the lowest temperatures at which a QTH lamp typically operates. The QTH lamp was analysed within the numerical model and it was shown that convection on the outside of the lamp is the driving factor which defines the radiative efficiency of the source. Based on this, an explanation for the high thermal efficiency was provided based on the divergence of the radiative and convective HTC's with an increase in temperature of the filament. Finally, a new efficiency curve was developed to allow the estimation of the efficiency of similar QTH lamps through measurement of the filament temperature.

9.1.2 Optimisation of the FIRH using MCRT and GA

A 2D prototype model was developed to allow the prediction of the thermal performance of a FIRH. Several assumptions were made during the development of this model, which reduced the accuracy of the simulations but allowed the automated design process to be validated early in this work. An optimised FIRH was developed using the automated design process, manufactured, and shown to outperform commercial units in terms of thermal performance and reduced reflector size. The Au-coated version of this device was measured to produce a higher heat flux output than the theoretical maximum for a convex tungsten source. An explanation for this was provided based on the process of light recycling, which can increase the performance of the source through the exchange of power output for increased radiance. Despite the limitations associated with this 2D MCRT model, it played a critical role in the development of a device which provided considerable improvements over the traditional trial-and-error design techniques. Therefore, the assumptions applied during the development of this model are deemed reasonable for the initial design phase of a reflector, or in cases where computation power is limited.

A 3D MCRT model was subsequently developed, rigorously validated, and shown to predict the output of the FIRH to within the uncertainty of the experimental measurements. This indicates that the modelling strategy employed is suitable for this problem type and can be used to model similar problems sets. A new Bézier-ray intersection algorithm was developed, which is sufficiently fast and accurate to test thousands of Bézier ray intersections per second. The algorithm is up to two orders of magnitude faster than the methods implemented from the literature and allowed the optimisation algorithm to be performed with the necessary population size.

The GA based optimisation process was investigated using the Taguchi experimental

design method to select the most suitable settings for this problem type. The population size of the GA, elite count, crossover function and crossover fraction have been shown to influence the result of the optimisation process. With a small population size, the GA was prone to becoming trapped in local optima and, in many cases, did not find the global optimum. For a cubic Bézier curve, a population size of 500 was established to find a near-optimum solution consistently although smaller population sizes are viable where computational power is limited.

Reflectors were optimised for a range of QTH sources and compared to the performance of commercially available FIRHs. It was shown that the optimised FIRHs for these sources brought significant improvements when compared with commercially available units or optimised ellipses: for the 750 W source, the optimised reflector provided greater than 200% improvement in heat flux and efficiency over the commercial unit and 50% greater than an ideal ellipse. A FIRH optimised for the larger 3000 W source also demonstrated similar improvements. The enhancement of radiative performance was also accompanied by a reduction in reflector size in all cases.

New theoretical limits for FIRH technology have been identified based on the light recycling principle and the maximum operating temperature of the filament. It can be concluded that the theoretical limits of FIRH technology are close to being met following this research, and therefore, an increase in the performance of the order of which was shown in this work is thought to be no longer possible without a corresponding improvement in the radiative output of the source. For applications that require higher intensities than the limits posed in this work, alternative technologies are suggested.

9.1.3 Design strategies for FIRHs

One of the most challenging aspects of designing a FIRH is the selection of the outlet size. Therefore, the development of design guidelines for outlet size was a primary research goal. Two methods for selecting the outlet size for FIRHs were proposed. These strategies utilise the geometry of the source to inform an outlet size depending on the heat flux and efficiency requirements of the application. For high heat flux applications with a cylindrical source, an outlet radius which is approximately equal to the radius of the cylinder source is suggested. This is referred to as a dilution-optimised reflector which maximises heat flux output while maintaining a reasonable efficiency. For applications which do not require high heat flux, a method was proposed to optimise the heat flux and efficiency simultaneously and obtain a

balance between these two metrics.

One of the principal issues highlighted during the early stages of this work was that it is challenging to compare FIRHs of different source and outlet geometries. This was addressed by developing nondimensional metrics which are normalised by either the étendue or skewness limits. This provides a more representative evaluation of the performance of a reflector and allows FIRHs with different source geometries and outlet sizes to be compared.

9.2 Future work

Based on the findings of this work, the following areas of future research are suggested:

9.2.1 Improvements to the design and manufacturing process

Several minor improvements to the design, manufacture, and finishing process are possible, which when combined will likely result in worthwhile improvement in the performance of the FIRH. These are as follows:

1. During the buffing process, the edges of the reflector bevel and form a radius. This radius is a deviation from the ideal shape and will reduce the efficiency of the reflector. This can be remedied through employing a cover plate to maintain the integrity of the corners or by the machining of the radius after the rough polishing process. This will require adding surplus material to the reflector to allow the desired shape to be obtained after machining.
2. The manual buffing process can be improved by employing an electro polishing or chemical polishing process. This will provide a more consistent and smoother finish than is possible with the approach employed in this work.
3. Higher-order Bézier curves will provide a non-negligible improvement to the performance of the reflector. This will require a larger GA population size to allow the optimal shape to be found more reliably or the use of other constraints to ensure the continuity of the reflector surface and convergence in a more timely manner.

9.2.2 Improvements to the model

The model assumes that all radiation absorbed into the quartz is lost. In reality, a proportion of the radiation absorbed into the quartz will be re-emitted. To account for this,

a more comprehensive model could be developed which includes the effects of convection to the ambient air from the quartz envelope. A HTC for the outer surface can be derived from the modelling strategy employed in Chapter 3 and integrated into the model without a significant increase in complexity or computation time.

A more accurate representation of the filament could be developed by following on from the work described in Appendix C.3.1. A vast improvement in speed of tracing is required before this method can be used. This may be achieved by using matrix operations to carry out the intersection tests or other similar simplifications to the tracing operation.

The supports of the filament could be taken into account to improve the model by employing additional primitive shapes. The process of modelling a source in MATLAB could be greatly enhanced by the development of a method to import CAD geometries directly into the model. Further improvements to the model data can be garnered through the testing of the reflectivity of the reflector surface materials across the entire wavelength range of interest and testing the quartz envelope of the lamp for absorptivity.

This work has focused entirely on rotationally symmetric shapes; however, there is evidence to suggest that nonrotationally symmetric reflectors can provide improved performance. The study of nonsymmetric shapes will also translate a wider range of related applications that were not the primary focus of this work, such as the uniform heating of large target surfaces. The VDPM Bézier-ray intersection algorithm developed in this work will be particularly pertinent to research in this area.

9.2.3 Development of FIRHs using alternative sources

Alternative lamps could be investigated for use in the further developments of FIRHs. The 1000 W lamp, while having a high power density and low cost, has the drawback of poor consistency and symmetry. This results in a considerable variation between the lamps received from the supplier in regards to performance when tested within the FIRH. The 750 W lamp employed in this study appears consistent and has a high power density. The lamp should be first characterised using methods outlined in Chapter 3 before the development of a FIRH.

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Appendix A

Solid State Additive Manufacture of Highly-Reflective Al Coatings Using Cold Spray

This chapter details research carried out during the early stages of this work regarding the manufacture of highly reflective coatings using cold spray.

A.1 Introduction

Cold spray (CS) is a coating and additive manufacturing (AM) technique where metal powders with diameters in the range of 10-50 μm are accelerated to supersonic speeds using a De Laval nozzle before impacting upon a substrate [1, 2]. The kinetic energy of the particle upon impact causes substantial plastic deformation of both the particle and substrate allowing bonding to occur through mechanical interlocking and adiabatic shear instability [2, 3]. A schematic of the CS process with a De Laval nozzle, substrate, and powder injector is shown in Fig. A.1. CS allows coatings to be manufactured which show little oxide inclusion, exhibit low porosity, and are free from melting and hence adverse changes in microstructure. These attributes allow the manufacture of coatings with properties similar to those of the feedstock powder. Other distinguishing characteristics of cold spray are the ability to rapidly manufacture thick coatings or complex free-standing shapes with build rates up to an order of magnitude higher than other coating and AM technologies [4, 5]. CS has been successfully applied to the deposition of a wide variety of materials for different applications including Al, Cu, Ti and their alloys, WC-Co, super-alloys, metal matrix composites and others onto

various substrates including steel, Al, Cu, and others [6–17].

Al and Al-based alloys have high spectrally averaged reflectivity values ($>90\%$) in the visible and near-infrared wavelength range [18] which deems these materials highly suitable for the cost-effective manufacture of reflective coatings when compared to other candidates such as Ag and Au. There are a number of methods by which metallic coatings can be manufactured such as chemical vapour deposition [19], laser cladding [20], hot dipping [21], electroplating [22], sputtering [23], and the sol-gel method [24]. However, reflective coatings are typically manufactured with sputtering, electroplating or chemical vapour deposition which create smooth, homogenous coatings with reflectance values which approach that of the theoretical maximum of the coating material. In recent work, Zhu et al. investigated the optical properties of plasma sprayed metallic coatings of Al, Cu and Ag [25]. The results show coatings with suitable bond strength and an average reflectance value of approximately 80% over the wavelength range of 1000-2500 nm for the Al coating. Other recent work has shown that optical properties of plasma sprayed cermet coating are affected by porosity, roughness, and grain boundaries [26–28].

CS, as a solid-state deposition process, has many advantages over the aforementioned manufacturing technologies. It is capable of producing coatings with high efficiency, short production time, little to no in-process oxidation and no coating thickness limitations. Furthermore, CS is particularly suitable for producing Al coatings due to Al's ductility and low yield strength. One of the primary issues with using CS to manufacture reflective surfaces is the porous and heterogeneous nature of the coatings. Porosity will be detrimental to the optical properties of the surface by increasing roughness and provide areas for the incident radiation to become 'trapped' within the subsurface layers of the coating. However, there have been many cases of almost fully dense Al coatings being CSed with high deposition efficiencies which would make candidate reflective coatings [29, 30]. Furthermore, there has been a lack of research focused on the optical properties of 'sprayed' metal coatings besides the work of Zhu [25]; thus this paper, for the first time, aims to determine if it is possible to manufacture reflective surfaces using CS and quantify the main factors which influence the optical performance of the coatings. As shown for plasma sprayed coatings, porosity, roughness and other surface defects will reduce the reflectance of the coatings and hence these factors will be the focus of in this research [25]. The gas heating temperature was the CS parameter investigated with an aim to reduce these defects by controlling the particle impact velocity.

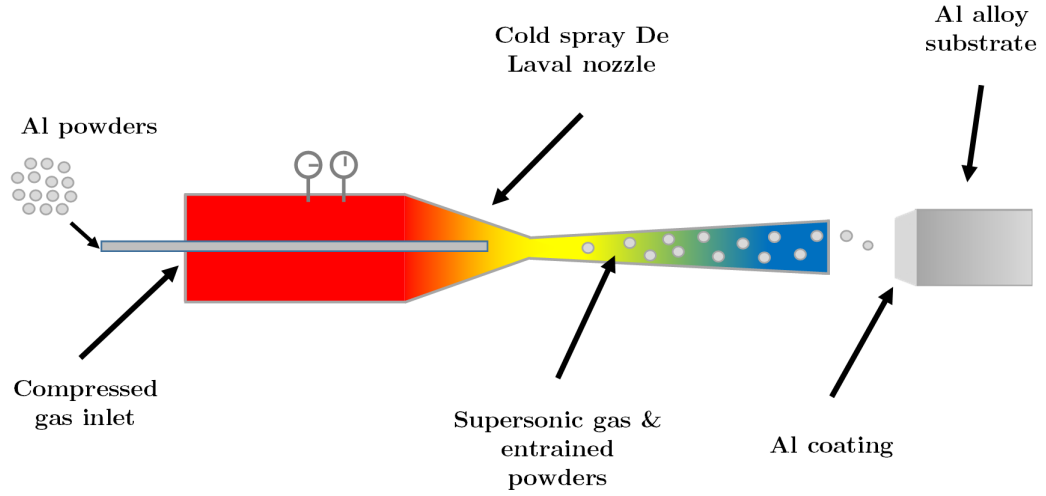


Figure A.1: Schematic of the CS additive manufacturing process.

A.2 Coating fabrication procedure

The reflective coatings were manufactured using the in-house CS system located at Trinity College Dublin. The CS system comprises of a De Laval nozzle, gas heater, CNC system, powder feeder, computer monitoring and control system, and gas supply. Nitrogen was used as the process gas for all experiments. The gas was heated before injection into the nozzle head using a high-temperature gas heater and six gas heating temperatures ranging from 300 °C to 550°C in 50°C intervals were studied. The compressed gas at 30 bar is introduced into the nozzle, and the powder is fed into the nozzle throat through the powder injector as shown in Fig. A.1. The gas and entrained powder enter the converging-diverging De Laval nozzle which accelerates the powders to supersonic speeds. High purity Al (H-30, >99.7% Al, Valimet Inc., California) was used in this investigation at a feed rate of 60 g/min. The impurities of the H-30 powder are specified to be no more than 0.3% consisting of by weight <0.2% Fe, <0.2% oil and grease, and <0.1% volatile mix. Fig. A.2 shows the surface morphology and size distribution of the Al powders used which was measured using a laser diffraction particle analyser (Horiba LA 920).

A nozzle cooling jacket was employed during this investigation (similar to the device used by Wang et al. [31]) to prevent clogging of the nozzle at high temperatures. The coatings were sprayed onto 30 mm diameter x 25 mm height billets of Al 6082 T6 alloy substrate which had an average surface roughness of approximately 500 nm after machining. The choice of the substrate was primarily a function of the ease of manufacture of the billets and

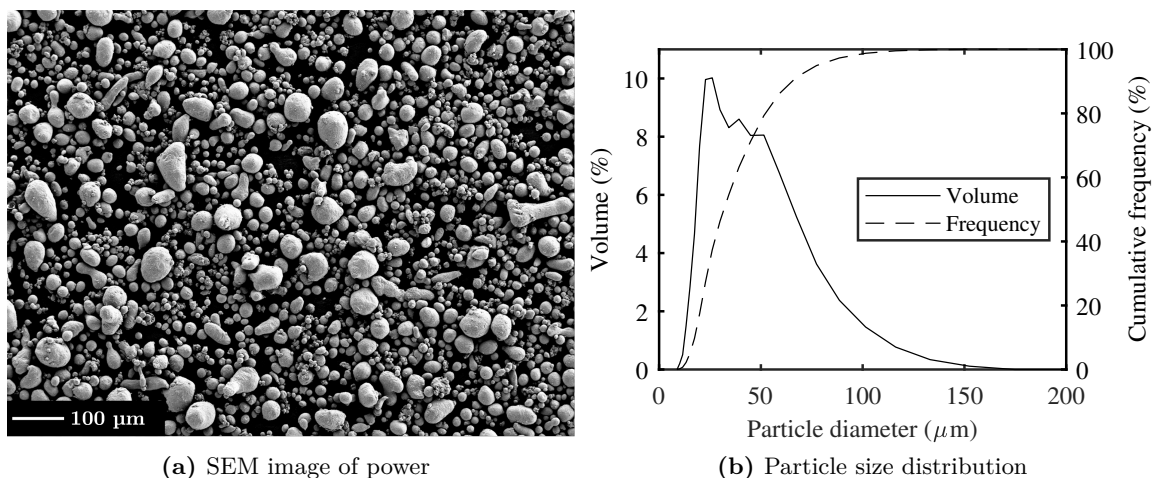


Figure A.2: Feedstock powders analysis.

material availability; however, other substrates could equally be used for this application since the adhesion of Al to various metals, polymers and ceramic with high bond strength has been widely reported [15–17, 30, 32–34]. All samples were sprayed at a traverse speed of 100 mm/s and a step size of 5 mm using a bidirectional strategy. The number of passes on each sample was controlled to obtain a coating thickness of approximately 1.5 mm. Post cold spray, the coating thickness was reduced through grinding and polishing to approximately 0.5 mm thickness to remove the rough, undulating surface and to ensure that first layer interactions with the substrate would not affect the coating characteristics.

A.3 Coating characterisation

Before reflectivity and surface roughness was measured, the samples were finished using a Jean Wirtz Phoenix 4000 polishing machine. Samples were ground/polished using P180 grit, P1200 grit, 6 μm diamond suspension, 1 μm diamond suspension, and 0.06 μm colloidal silica suspension for a total time of 1-2 minutes (until the correct coating thickness was obtained), 3 minutes, 3 minutes, and 10 minutes respectively at 150 rpm and 2 bar sample pressure. The polishing process was developed based on the recommended procedure and materials from MetPrep (UK). Unpolished samples were not evaluated due to the unsuitable nature of the rough surface for use as a reflector in the as-fabricated state. Reflectivity measurements were carried out using Perkin Elmer Lambda 900 between the visible and near-IR wavelength range of 400 to 1800 nm in steps of 0.5 nm with the UV/Visible and near-IR detector change occurring at 860 nm. The sample's spectrally averaged reflectance was calculated as the mean

reflectance value across the wavelength range tested. Finally, the measurement error of the spectrometer was determined to $\pm 0.65\%$ by obtaining five spectrally averaged measurements of a single Al sample.

The average surface roughness (S_a) of the polished coatings were measured using a white light interferometer (WLI, Filmetrics, Profilm 3D) using a magnification of $10\times$. Five images randomly located on the surface were averaged to find the S_a using ISO 25178. The data was first adjusted to level the surface and then outlier points with a slope of greater than 60 degrees were removed and filled.

Porosity was also inferred from relative density measurements carried out based on the Archimedes principle:

$$\rho_{relative} = \frac{\rho_{coating}}{\rho_{bulk}} = \frac{\rho_{water} \cdot m_{coating(air)}}{\rho_{bulk} \cdot (m_{coating(air)} - m_{coating(water)})} \quad (A.1)$$

where, $\rho_{coating}$ is the density of the CS sample; ρ_{bulk} is the measured density of a bulk Al sample which was determined to be 2.70 g/cm^3 using the same method; $m_{coating(air)}$ is the weight of CS sample in air; $m_{coating(water)}$ is the weight of CS sample in water; ρ_{water} is the density of water. The CS samples were removed from the billets using a lathe after removal of the top surface to produce a ‘coin’ shape from which the density can be accurately measured. A single deposition efficiency measurement for each process parameters was determined using the ratio of the deposit weight to the total weight of powder delivered through the powder feeder for a 40-second spray time. Coating cross sections were characterised in the SEM by first mounting and polishing using a similar polishing procedure used for the reflective samples. Etching was carried out by exposing coating cross sections to Keller’s reagent for 2-3 minutes. The flattening ratio is a measure of particle deformation and is defined as the ratio of the diameter of a splat to the diameter of a sphere of the same volume [2, 35]. The flattening ratio was determined from SEM images of etched cross-sections of three representative gas heating temperatures using 10 randomly selected particles that had clearly identifiable boundaries.

A.4 Results and discussion

A.4.1 Reflectivity and coating microstructure

The total reflectivity vs wavelength data of selected polished samples and the bulk Al comparison is shown in Fig. A.3, while a photograph of a polished cold sprayed Al surface at 300°C is also included. Notably, the reflectance of all of the coatings drastically drops at 800 nm which corresponds to the reported absorption band of Al [36]. Overall, there is a clear trend between the CS gas heating temperature and the coating reflectance for the samples shown: the surface reflectance incrementally decreases with an increase in gas heating temperature across the entire wavelength range. The 550°C sprayed sample had the lowest average reflectance while the 300°C sprayed sample had the highest average reflectance with the 450°C sample bisecting the two curves. In addition, the bulk Al sample has the highest reflectance of all the tests as expected due to the lack of surface porosity and defects. The reflectance of the bulk Al sample compares well with published literature for Al at room temperature with a local minimum at ~ 820 nm of approximately 86% (vs 86.3%) and a local maximum of 96% (vs 97.2%) at 1800 nm [36]. The 300°C sprayed sample has a reflectance quite close to that of the bulk sample throughout the near infrared wavelength range. However, the difference between the samples is more significant in the UV range. This may be due to the presence of small-scale defects on the surface of the coatings which absorb incoming radiation more prominently in the UV range than the near IR range. Shorter wavelength will be absorbed or scattered more readily than longer wavelengths as given by Mie theory.

The spectrally averaged reflectance of each sample versus gas heating temperature is provided in Fig. A.4. The maximum average reflectance was 93.4% for the 300°C, and the minimum average reflectance was 90.4% for the 550°C sample indicating that a lower gas heating temperature is optimal for producing highly reflective coatings with this setup. The remaining samples followed a linear decrease as the gas heating temperature was increased with the exception of the 350°C sample. It noted that the difference between each of the samples was visually quite clear with the highest reflectance sample appearing very close to a mirror with only minor surface defects while with the 500°C surface defects were apparent throughout the surface. The reflectance values provided in Fig. A.4 show that a highly reflective surface can be manufactured with CS which approaches the reflectance of that of bulk Al with the bulk sample being 1.2% more reflective than the coating sprayed at 300°C. The difference between the samples is not within the experimental uncertainty of the

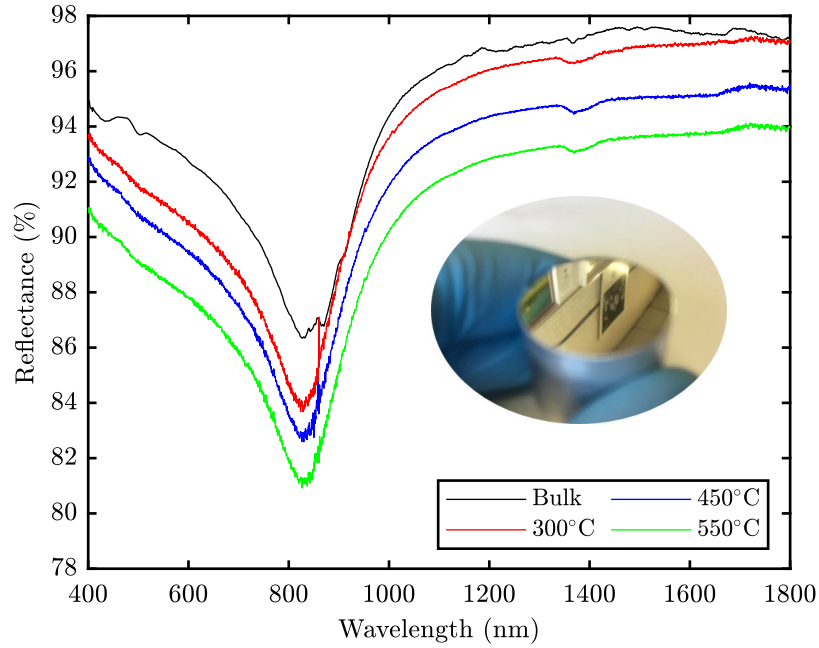


Figure A.3: Total spectral reflectivity data for various gas heating temperatures and bulk Al with polished sample preparation. An image of 300°C gas heating CS sample is also shown.

spectrometer ($\pm 0.65\%$) but, overall, is quite insignificant in terms of absolute reflectance. In the authors' opinion, with further work and improved selection of powders, cold sprayed reflective surfaces with the reflectivity of bulk Al are achievable. This will be discussed further in section 9.3.2. When compared to the data presented by Zhu et al. [25], the highest reflectance is a significantly improved with 93% reflectance at 400-1800 nm versus 80% at 1000-2500 nm, although it must be considered that no post process polishing was carried out by Zhu et al. in their research.

In order to understand the reflectivity trend, polished, etched, and etched binary counterpart cross-sectional SEM images of a selection of samples are presented in Fig. A.5. It is clear that there is an increase in porosity of the coatings as the gas heating temperature is increased as there are pores and defects visible throughout the coating at the highest gas heating temperature tested (550°C, Fig. A.5c). This supports the reflectivity data in Fig. A.4 as an increase in surface porosity will obviously lead to decreased optical performance. The etched cross sections and corresponding binary images (Fig. A.5d-i) show substantial deformation of the particles at the lowest gas heating temperatures tested and comparatively less deformation as the gas heating temperature is increased. In order for inter-particle voids to be filled and a dense coating manufactured, it is critical that high strain rate deformation occurs upon particle impact and impact from subsequent particles [37]. The flattening ratio

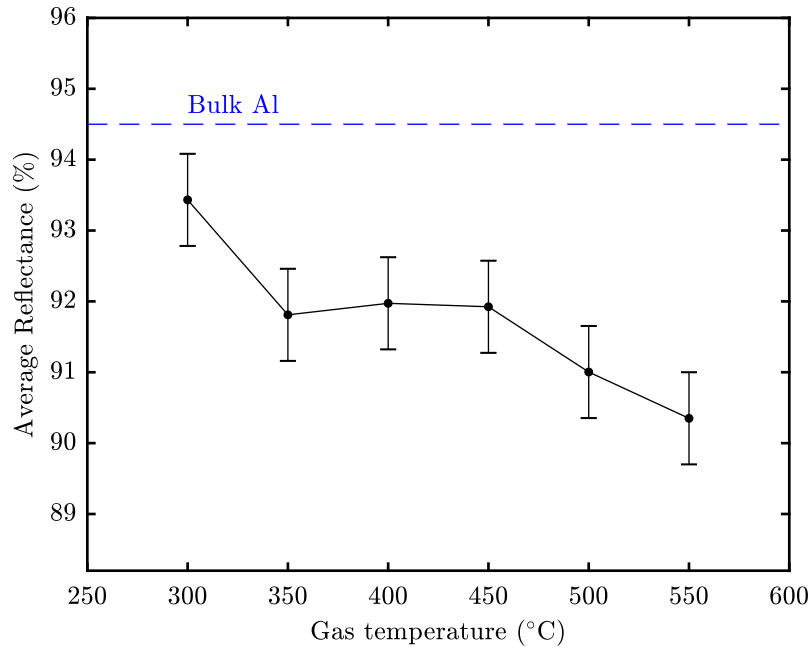


Figure A.4: Average reflectance values versus the gas temperature.

was determined to be 1.98, 1.89, and 1.74 for the gas heating temperatures of 300°C, 400°C, and 550°C respectively which highlights the disparity in deformation which occurs across the range of gas heating temperatures tested. It is clear that particle deformation and highly dense coatings lead to improved reflectivity as pores and defects will promote the incident radiation becoming ‘trapped’ within the subsurface layers of the coating instead of reflecting upon the upper reflective surface.

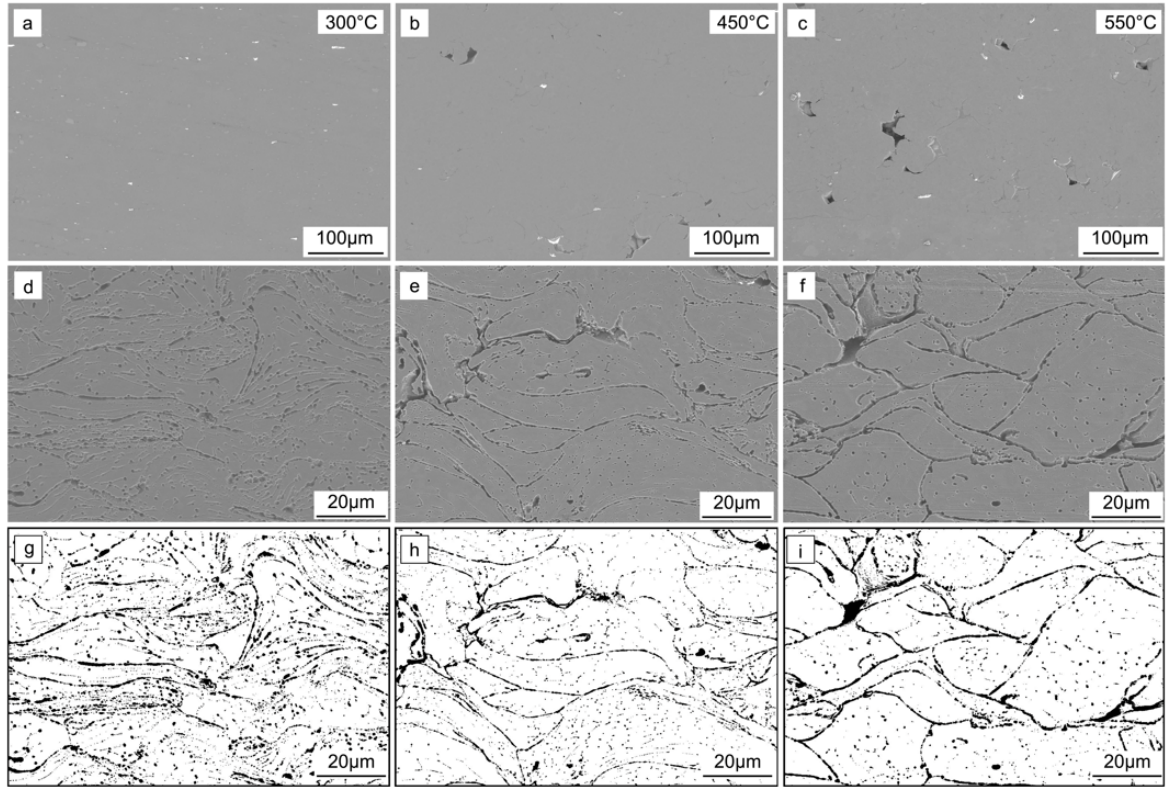


Figure A.5: Cross-sectional SEM images of coatings produced at 300°C, 400°C and 550°C. (a-c) polished cross-sections, (d-f) etched cross sections and (g-i) etched binary counterparts

A.4.2 Effect of coating porosity and surface roughness on the coating reflectance

From Fig. A.5, it is apparent that the porosity of the coating increases with gas heating temperature; however, the variation in porosity across the coating surface can lead to large uncertainties when quantifying using 2D cross-sectional images. Therefore, the porosity was measured using the Archimedes water balance method which accounts of the entire volume of the coating and thus is a more representative approach with lower uncertainty. Fig. A.6 shows the effect of gas heating temperature on the coating porosity and deposition efficiency. The porosity data supports the reflectivity data in Fig. A.4 and the cross-sectional images in Fig. A.5 as an increasing porosity level will result in a greater probability of absorption of incident radiation within surface defects. The lowest bulk porosity of 0.72% corresponded with the highest average reflectance (93.4%) and the highest bulk porosity measurement corresponded with the lowest reflectance value measured (90.4%), highlighting porosity's influence on reflectance. Typically, when CSing high-ductility materials (such as Cu), increasing the gas heating temperature and pressure will reduce the coating porosity

due to the increased particle impact velocities [38]. However, in this work, the experimental results indicate that the coating porosity of CS Al increases with increasing the gas heating temperature. This trend is explained by the effect of the particles which do not deposit to form a coating: when the DE is low, there are many particles which impact the coating and densify the coating which is referred to as tamping. However, as the impact velocity and DE is increased, the increase in particle impact velocity is not high enough to offset the drop in tamping; therefore the density of the coating decreases. This trend is explained in further detail in the author's previous work [39] with experimental data over a wider range of particle impact velocities and comparisons to a numerical model.

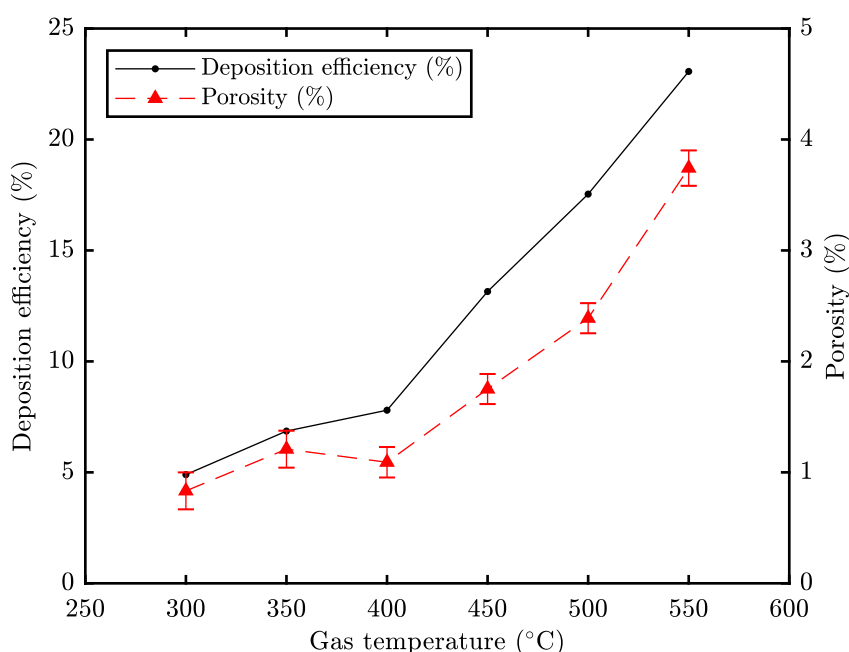


Figure A.6: Coating porosity and deposition efficiency versus the gas temperature

As expected, an increase in gas heating temperature increases deposition efficiency which is typical of cold spray: increasing the gas temperature will enhance the sonic velocity of the gas and in turn increases the particle impact velocity. This allows more particles to exceed the critical velocity and deposit to form a coating. Additionally, the heated gas transfers thermal energy to the in-flight particles which reduces the critical velocity through thermal softening. Increased deposition efficiency is favourable as the processing cost is reduced and the build rate increased: the deposition efficiency rose from 5% to 23% for gas heating temperatures of 300°C and 550°C respectively as shown in Fig. A.6. However, the porosity of the coatings also increased within this temperature range. The coating porosity should

be minimised to increase optical performance, and hence the lowest gas heating temperature test is the optimal operating point. However, this set point is inefficient in terms of gas and powder usage as the majority of powder exiting the nozzle fails to bond with the substrate or coating. The literature provides many examples of deposition efficiencies of above 60% at 700 m/s for pure Al which is in contrast to the deposition efficiency of 15% obtained in this experiment at similar velocities [30, 32]. Smaller powders with a more favourable size range were utilised in the aforementioned references, and therefore it may be the case that an improved powder selection is required for future work on this topic.

Porosity, among other factors, will influence the surface roughness of the coatings, as the craters associated with bulk porosity will result in surfaces that are below that of the mean S_a value. This will tend to increase the value of S_a , but the deviations are due to porosity rather than random variation upon the top surface. With a rough undulating surface (large S_a value), incident radiation is more likely to be absorbed due to multiple reflections on the surface; thus a smoother surface is preferential to increase the total reflectivity. In addition, for specular reflectivity, a smooth surface is also required to ensure incident radiation reflects at the consistent angle to maintain image directionality. Due to the heterogeneous nature of CS coatings with porosity, there is variation in roughness across the surface which poses great difficulty in measuring S_a with a high degree of certainty even at low magnifications; therefore five randomly located images were taken on each of the surfaces to determine average surface roughness and reduce uncertainty.

Fig. A.7 shows the gas heating temperature versus surface roughness and reflectivity. There is no clear relationship for the gas heating temperature versus surface roughness data besides the maximum S_a value corresponding the minimum reflectance; the S_a actually decreased as the gas heating temperature was increased from 350 °C to 450 °C. The minimum S_a value obtainable will be determined by the polishing procedure, the mechanical properties of the material and, as discussed, the surface porosity. However, the primary factor which will limit the lowest surface roughness obtainable for CS coatings will be the porosity as pores cannot be removed or reduced through polishing. In addition, due to the significant disparity between the top surface roughness and the depth of surface pores and the steep angles of the pore walls, the WLI could not accurately capture the entire pore, and this missing data was filled during post-processing which results in the inaccurate measurement of the surface roughness. Therefore, the surface roughness cannot be accurately quantified by the WLI when measuring a highly porous surface with steep crater walls such as is found

at the highest gas heating temperatures. However, it can be concluded that surface porosity is the dominant factor which determines the reflectivity of a CS coating and S_a should be used as a surface quality metric when comparing highly dense coatings with little surface porosity.

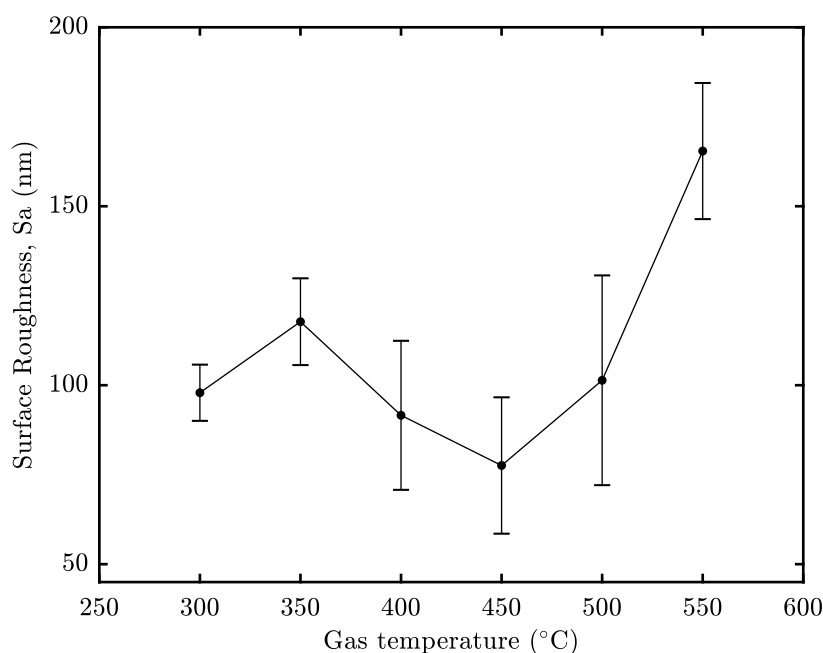


Figure A.7: Surface roughness and average reflectance versus the gas temperature

A.5 Conclusions

Several Al coatings were CSed using commercially pure feedstock at various gas heating temperatures. The primary aim of this research was the discovery of the effect of CS parameters on the optical properties of the coatings and determine if it is possible to manufacture reflective coatings using CS. Hence, the manufactured coatings were quantified with respect to reflectance, porosity, and surface roughness. The reflectance of the coatings sprayed at the lowest gas heating temperatures approached the reflectivity of bulk Al (93.4% vs 94.5%), and higher reflectance values could be achieved with follow-on work and improvements to the selection of feedstock powder. The CS coatings with higher porosity were shown to decrease the reflectance of the surfaces, and the porosity of the coatings increased from 0.72% to 4.44% for the lowest and highest gas heating temperatures respectively. Porosity was found to be the dominant factor which influences the surface roughness and hence reflectivity of the

coating. Finally, this research has shown that highly reflective coatings that approach the optical performance of bulk materials can be additively manufactured using cold spray with build rates significantly higher than competing techniques and this is potentially a suitable process for the manufacture of custom reflectors when coupled with another process such as casting or alternative high precision additive manufacturing processes.

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Appendix B

Rapid heat treatment using the optimised FIRH

In this section, details of the integration of the FIRH into a manufacturing chain of the CS process, and an investigation of the effect of a rapid heat treatment on the mechanical properties of the coatings will be discussed

B.1 Introduction

As outlined in the literature review, CS is a solid state additive manufacturing process which relies on the high velocity impact and deformation of the particles for the manufacture of coatings and bulk components. In the as-sprayed state, CS samples are considerably more brittle when compared to bulk counterparts due to the strain hardening which occurs during deposition. This adversely affects the fatigue strength of the coatings and their suitability for mechanically stressed applications. Additionally, CS relies on the deformation of the impacting particles and substrate in order to form mechanical and metallurgical bonds; however, materials which deliver a high strength-to-weight ratio are less likely to deform during the deposition process and therefore typically result in lower interparticle bond strength. Therefore, heat treatment processes are often employed to negate defects, improve interparticle bond strength and overall mechanical properties of CSed aluminium coatings [1, 2] and other materials [3, 4].

A full anneal or stress relief operation requires considerable processing time due to the large bulk which must be heated, held at a specified temperature (or temperatures), and subsequently cooled for a single heat treatment cycle. Also, heat treatment of a whole

component is in some cases not possible, for example, when heat treating a component repaired by CS where dissimilar materials compose the original component and the repair material.

Previous work by the author has investigated using a custom FIRH to heat treat small samples of CSed materials, showing augmentation of the mechanical properties at particular heat treatment parameters [5]. This section of the work will expand on this early work to investigate if a FIRH can be successfully integrated into the CS chain and if the performance of the device (i.e. power and heat flux output) is sufficient to induce changes in the mechanical properties of a bulk CS part.

B.2 Integration of FIRH with CS

The first step to testing the FIRH with the CS is to assimilate it into the CS chain allowing the manufacture and heat treatment of materials concurrently. The CS system is composed of a de Laval nozzle to accelerate the gas and powders, a gas heater, cooling jacket, powder feeder, gas supply, and control and data acquisition equipment. The nozzle, gas heater, and cooling jacket are shown in Fig.B.1.

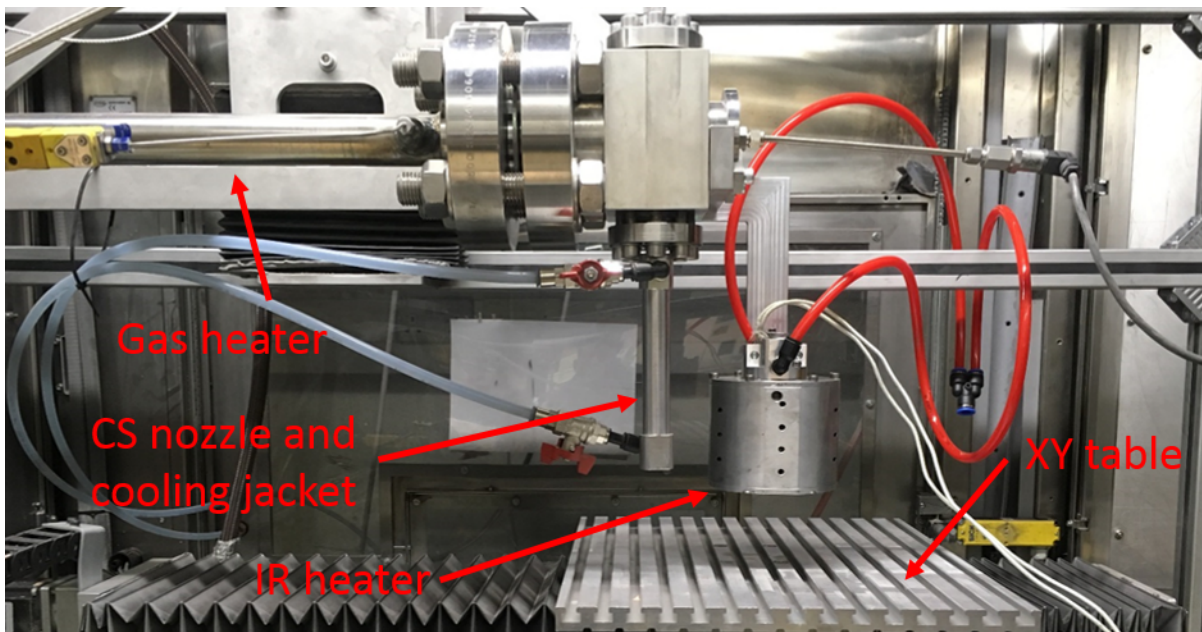


Figure B.1: Photograph of the FIRH integrated within the CS processing chain.

B.3 In-process heat treatment

B.3.1 Experimental setup

B.3.1.1 Coating fabrication procedure

The coatings were manufactured using the in-house CS system located at Trinity College Dublin. Nitrogen was used as the process gas for all the experiments undertaken in this research at a single gas heating temperature of 700°C using high purity aluminium 6061 (A6061-40A3 Toyal, Japan). All samples were sprayed at a traverse speed of 200 mm/s and a standoff distance of 40 mm. A bidirectional spray strategy was employed with a hatch distance of 5 mm. The second layer was offset by 2.5 mm such that each layer was sprayed in between the two hatches of the previous. The final thickness of each coating was between 6 and 7 mm for a total spray time of approximately 7 minutes.

Table B.1: Cold spray processing parameters

Process gas	Inlet pressure	Gas temperature	Traverse speed	Standoff distance	Powder feed rate
Nitrogen	3 MPa	700°C	200 mm/s	40 mm	60 g/min

B.3.1.2 Heat treatment procedure

A schematic of the manufacturing and heat treatment processes are shown in Fig.B.2. A rapid heat treatment was carried out using the Au GA optimised FIRH described in Chapter 6. The power level of the unit was set to 130 W emanating from the 10 mm diameter exit located 1-3 mm above the surface being treated. This power level was chosen as this is the highest power output which can be sustained for long periods from the FIRH as concluded in Chapter 5. The heat treatment was carried out in process at two speeds of 10 and 40 mm/s after every layer deposited by the CS following the same path as the CS nozzle. The total time for the heat treatment process was 35 and 140 minutes for the 40 mm/s and 10 mm/s samples, respectively.

B.3.1.3 Mechanical testing procedure

The CS samples were removed from the substrate and cut into five dog bone samples using a wire EDM (Excetek V400G, Taiwan). The tensile test samples were cut to a gauge length of 25 mm, a width of 5 mm, a thickness of 4 mm and an overall length of 54 mm. The ultimate

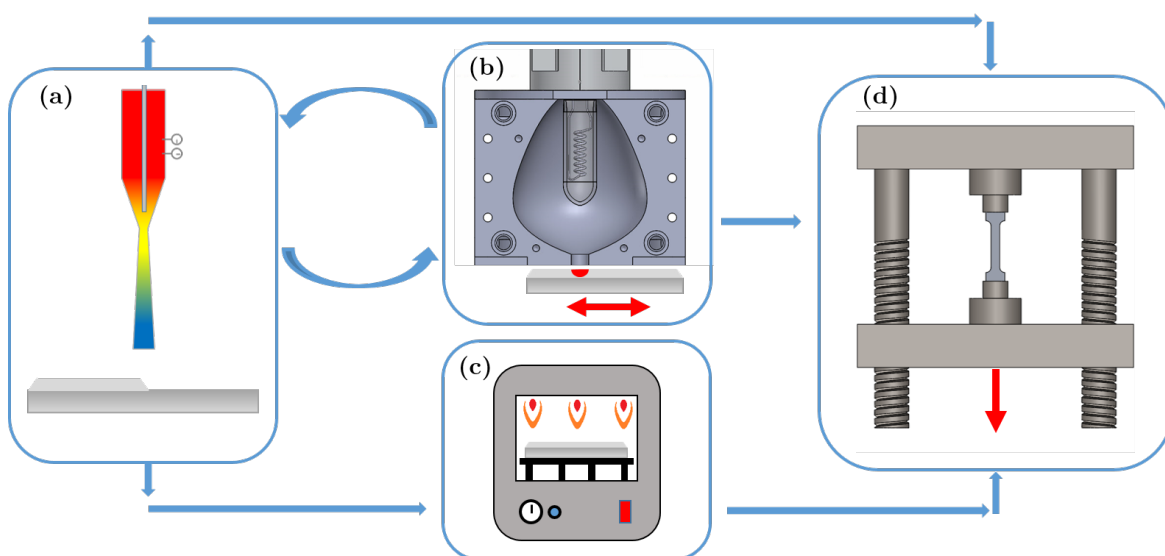


Figure B.2: Manufacturing process schematic with: (a) the cold spray coating manufacture, (b) rapid IR heat treatment, (c) traditional heat treatment, (d) tensile testing of dog bone samples

tensile stress (UTS) and elongation at failure (EL) of the deposits were determined based on the average value of at least three of tensile specimens. A number of the weaker dog bone samples failed during tensile test setup and were therefore omitted from the provided data. Tensile testing was carried out using a universal tensile strength system (Instron 3366, UK) at a displacement rate of 1 mm/min.

B.3.2 Results and discussion

The effect of the heat treatment on the micro-hardness of the samples is presented in Fig. B.3 and shows a trend of a reduction in hardness with an increase in heat treatment time. The as-sprayed sample is the second hardest of all the specimens tested only exceeded by the 40 mm/s rapid heat treatment test. However, this is within the uncertainty of the hardness measurement, and it is anticipated that the as-sprayed sample would be the hardest if the measurement uncertainty was reduced. The as-sprayed sample with an average Hv of 60 is significantly harder than the bulk of Al 6061 T0 which was measured to be 34 Hv. This is due to the work hardening of the sample which occurs during deposition and the uncontrolled cooling during powder formation. The fully annealed sample delivered the lowest micro-hardness of all the specimens tested, as expected, with a 49% reduction when compared to the as-sprayed sample. The stress relieved sample, which has a much shorter processing time than a full anneal, also shows a significant reduction in hardness by 44% when compared to the as sprayed sample. The rapid heat treatment process at 10 mm/s on average delivered

a 14% reduction in hardness. The 40 mm/s test did not have a measurable effect on the hardness of the sample based on the tests performed. Statistically, it is not conclusive with this sample if the rapid heat treatment had a significant effect on the hardness of the coatings, although, on average, the data suggests that the 10 mm/s test likely reduced the coating hardness. Further testing is required for conclusive evidence. The 40 mm/s traverse speed may be too high to cause a measurable effect using this technique, and therefore a higher power or slower speeds must be used in order to obtain measurable effects.

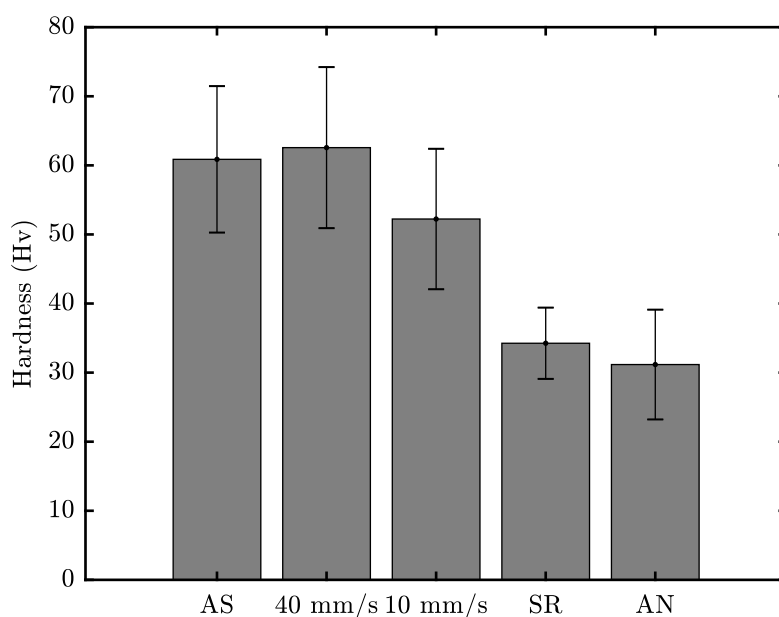


Figure B.3: The microhardness of the CS samples after various heat treatments.

The effect of the in-process and traditional heat treatments on the UTS of the coatings is presented in Fig. B.4. The as-sprayed samples failed at an average stress of 16 MPa which is considerably lower than that of the bulk material. This is due to the porosity of the coating and the poor interparticle bond strength which is delivered by the coating when sprayed with nitrogen at these processing parameters. However, on average, the UTS is improved for all of the heat treatment procedures carried out. The fully annealed sample delivered the largest improvement with an increase of over 110% in the UTS. The stress relieved sample, which had a much shorter heat treatment time, showed a similar increase in the UTS with over 105% when compared to the as-sprayed state. Both the in-process heat treatments also showed measurable improvements in the UTS of the coatings with a 24% and 52% increase in the UTS for the 40 mm/s and 10 mm/s traverse speeds, respectively.

The variation in the UTS also tends to reduce with an increase in the length of the heat treatment time indicating that any defects in the coatings are being repaired or interparticle bond strength is increasing. However, despite the decrease in the variability of the UTS, the variation across the samples is still quite large. This can be attributed to the porosity of the coating. In porous coatings, the failure will be dependent on the presence of large pores or groups of smaller pores which act as stress concentrations causing local yielding. In CS, the pores are not evenly distributed, and hence localised porosity may cause a specimen to fail prematurely. In order to decrease the variation between dog bone specimens from the same coating sample, a lower porosity coating should be manufactured by utilising higher gas velocities. It is also noted that the difference between the UTS delivered by the shorter 1 hour heat treatment is similar to that from the full anneal, which would suggest that longer heat treatments may not be required.

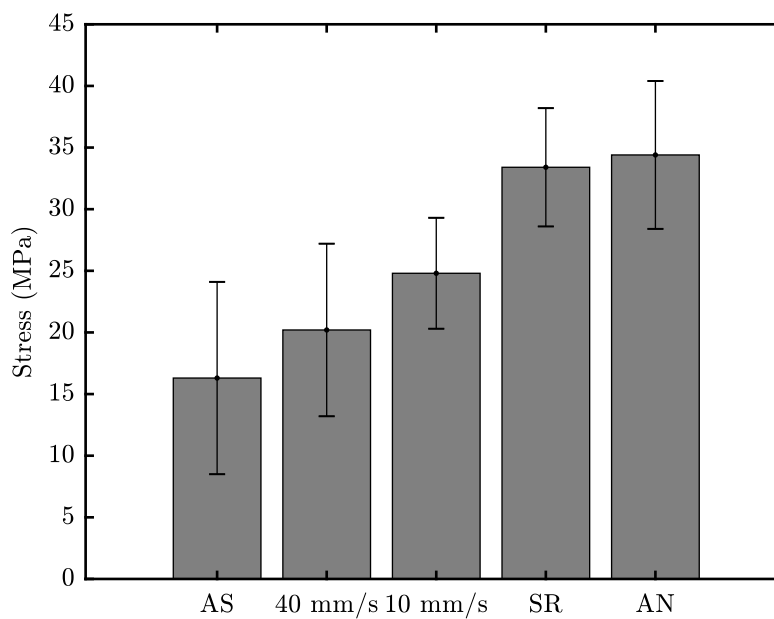


Figure B.4: The effect of various heat treatments on the UTS of Al 6061 samples.

A similar result is shown with the elongation at break of the specimens for various heat treatments as presented in Fig. B.5. The annealed sample again shows the greatest improvement with the elongation at break with a 114% increase on average for the 5 samples. The stress relieved sample delivers an improvement in the UTS with a 43% increase, indicating that the ductility of the coating may be more closely linked to the heat treatment time rather than the UTS and hence limited by the significantly shorter duration of the heat treatment.

On an average basis, the 10 mm/s in process heat treatment also improved the elongation at break by 43%, but the error bars encompass a significant proportion of this increase. However, the hardness data in Fig. B.3 and the UTS data in Fig. B.4 would suggest that the 10 mm/s test had a positive effect on the coating's mechanical properties. The 40 mm/s test on average has a slightly lower elongation at break when compared to the as-sprayed sample, although the confidence interval overlaps that of the as-sprayed sample. As discussed previously, this heat treatment traverse speed may be too low to provide a conclusive result given the experimental uncertainty.

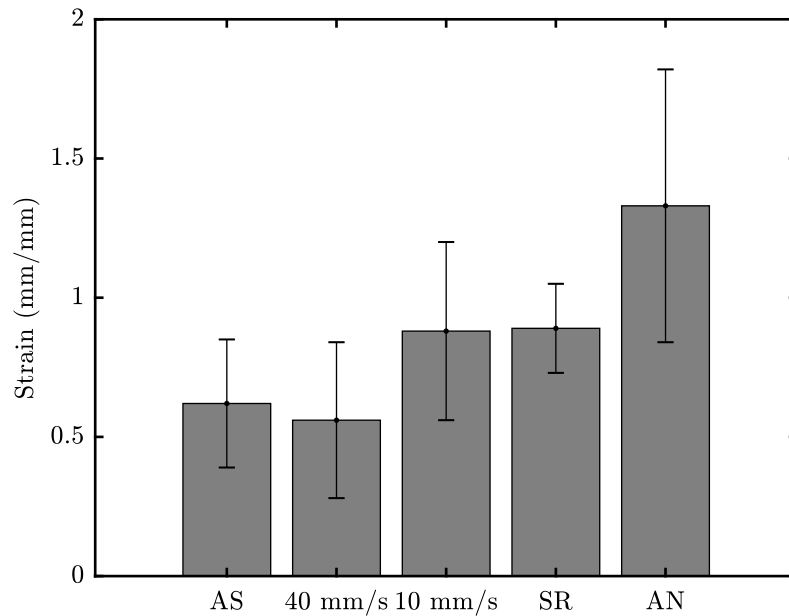


Figure B.5: The effect of various heat treatments on the elongation at failure of Al 6061 samples.

The effect of the IR heat treatment on the fracture mechanics of the CSed coatings is shown through SEM images in Fig. B.6. The as sprayed coating in Fig. B.6a displays brittle fracture behaviour with no evidence of deformation during the loading and failure regime. The annealed coating shows more evidence of deformation occurring during the tensile test with smearing evident on many of the particles at the fracture surface. The SEM image of the fractured coating heat treated with the focused IR device at 10 mm/s is encouraging with clear evidence of smearing of the particles, similar to the fully annealed sample. The 40 mm/s test shown in Fig. B.6d displays characteristics which more closely resemble the as sprayed test, which reinforces the tensile test data and that a lower speed is required to have any measurable effect on the mechanical properties of the coating.

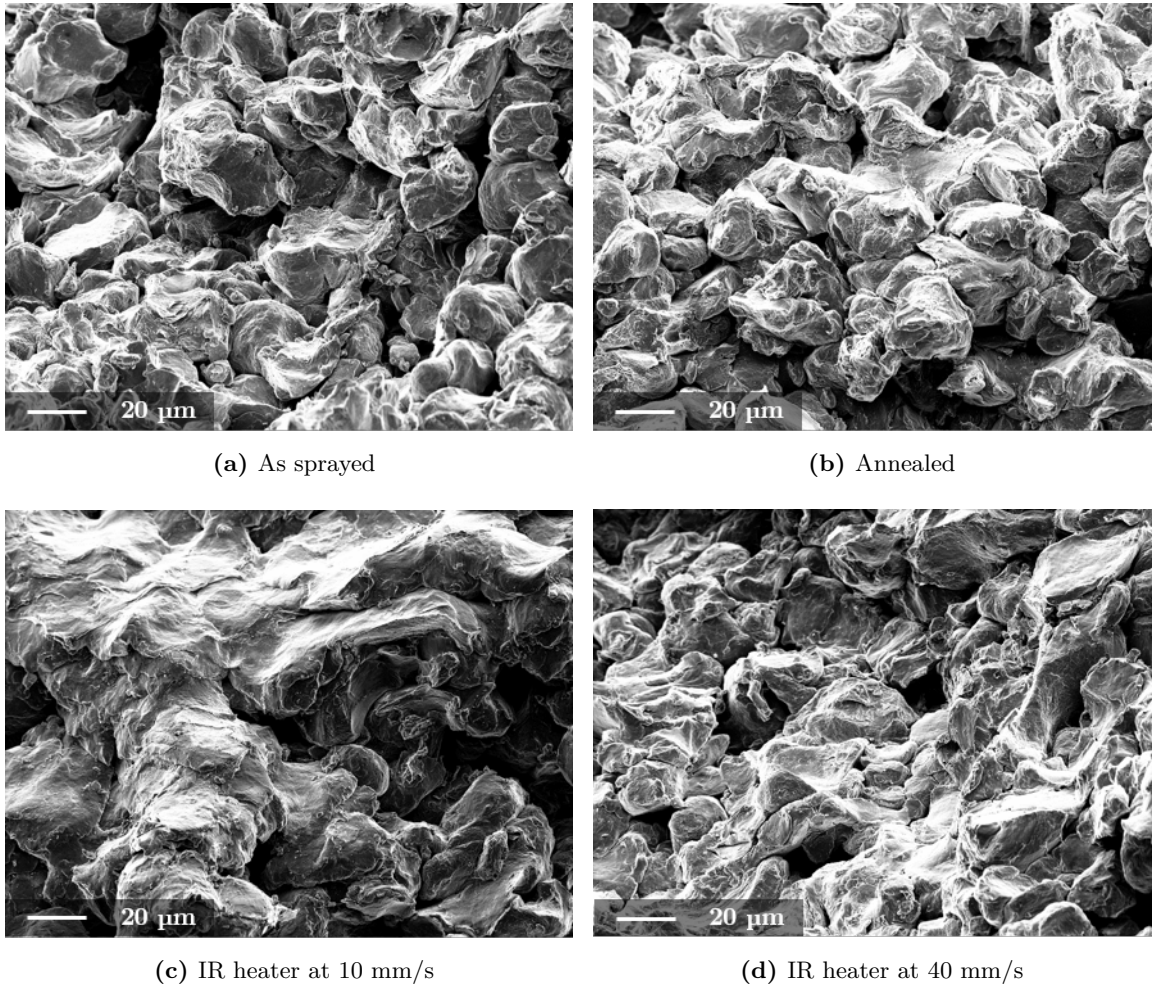


Figure B.6: Effect of IR heat treatment on the fracture behaviour of CSed materials.

Overall, this technique has shown promise in improving the mechanical properties of CS coatings in-process, potentially negating the need for the heat treatment of a component after manufacture. The method described is particularly suitable for the localised heat treatment of large components or components repaired by CS that are not possible to heat treat conventionally. However, several issues arose during the testing of the device CS which requires follow on research to address.

The coatings manufactured using the parameters outlined were too porous to draw strong conclusions regarding the efficacy of this process. Going forward, the cold spray process needs to be optimised to deliver improved coating properties.

Despite the CS nozzle being located above the outlet of the reflector and a positive pressure flow of compressed air out through the reflector, CS powder entered into the reflector chamber and attached to the surface of the QTH lamp. This led to the failure of the lamp

which damaged the gold coating of the reflector preventing further tests from being carried out and other heat treatment speeds from being tested. To use a FIRH with the CS process, a positive flow out the reflector enclosure is not sufficient due to the high velocity of the particles. A future version of the FIRH should employ a quartz cover plate to seal the entrance to the reflector and prevent inflow of powder into the reflector enclosure.

The performance of the device needs to be increased either through employing one of the optimised reflectors or by adjustment of the outlet size to achieve either higher power outputs or heat fluxes. An investigation is required to determine the benefits of improving either the heat flux or power output with regards to the heat treatment of the coatings. This study relies primarily on material science and metallurgy, which lies outside of the remit of this work.

Further details of this work can be found in the conference proceedings on the same topic in reference [6].

References

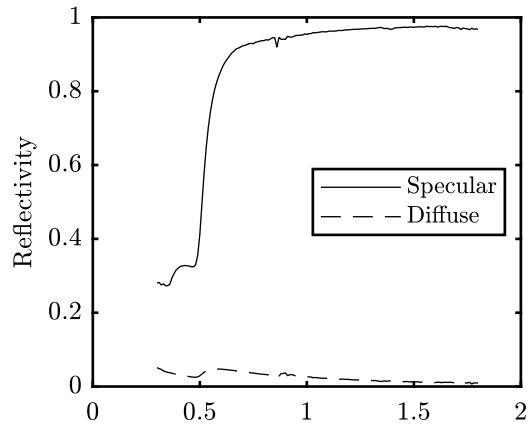
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Appendix C

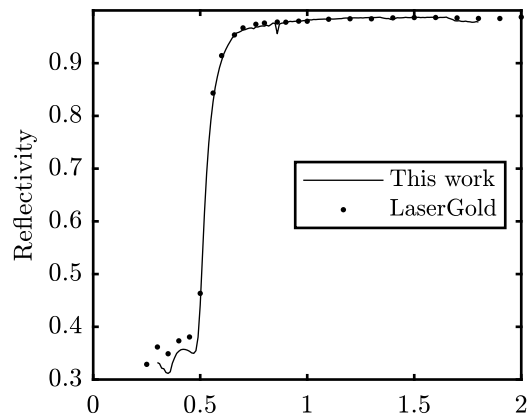
Supplementary information

C.1 Additional data

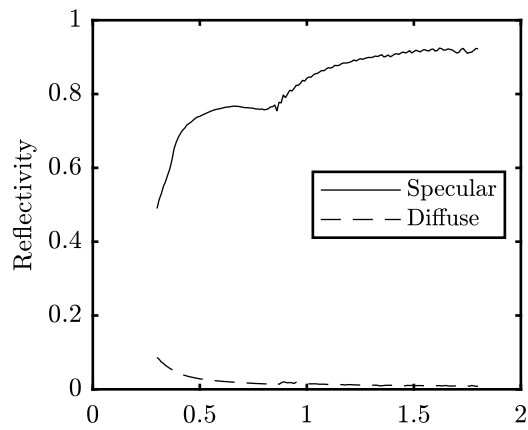
The reflectivity specular and diffuse data for the Al 6082 and Au material types are shown in Fig. C.1a and Fig. C.1c, respectively. Notably, the diffuse reflectivity increases at lower wavelengths due to the decrease in the relative size of the radiation wavelength in comparison to the defect feature size. Comparison to the Au data provided by Epner Technology in Fig. C.1b shows excellent agreement across the entire wavelength range of interest. The reflectivity of the Al material shown in Fig. C.1d shows lower reflectivity values than that measured in the previous work of the author [1] and other literature sources [2]. This can be explained by the fact that pure Al has a higher reflectivity than its alloys and that the polishing procedure employed in the author's previous work was a traditional polishing method which should provide a higher reflectivity. However, good agreement is shown between *Bartl et al.* [2] and the pure Al reflectivity measurement carried out by the author which validates the technique used.



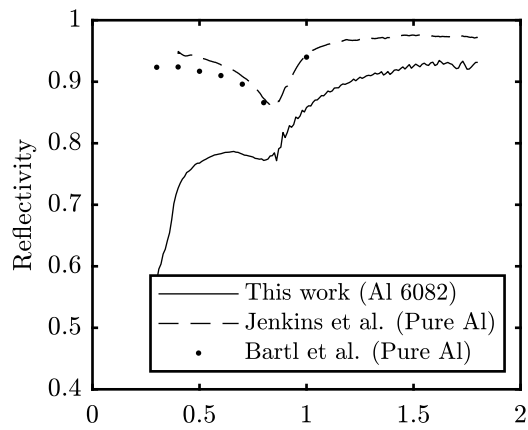
(a) Specular and diffuse reflectivity measurements.



(b) Comparison to coating manufacturers data.



(c) Specular and diffuse data.



(d) Comparison literature data.

Figure C.1: Reflectivity data for the Al and Au materials [1–3].

Table C.1: Material properties employed in the conjugate heat transfer model. The range which these properties are valid for has been included where available.

Material	Property	Value	Range	Source
Air	Viscosity, μ	$1.85 \times 10^{-5} \times (T/300)^{0.64874}$ Pa s	$100 < T < 10000$ K	[4, 5]
	Specific heat capacity, C_p	$951.71 + 0.19 \times T$ JK ⁻¹ kg ⁻¹	-	[6]
	Thermal conductivity, k	$0.0079 + 6.145 \times 10^{-8} \times T$ W m ⁻¹ K ⁻¹	-	[4]
	Molar mass, M	29 g mol ⁻¹	-	
Nitrogen	Viscosity, μ	$1.78 \times 10^{-5} \times (T/300)^{0.64874}$ Pa s	$100 < T < 10000$ K	[4, 5]
	Specific heat capacity, C_p	$993.1 + 0.161 \times T$ JK ⁻¹ kg ⁻¹	-	[6]
	Thermal conductivity, k	$0.0068 + 7 \times 10^{-5} \times T - 7 \times 10^{-9} \times T^2$ W m ⁻¹ K ⁻¹	-	[6]
	Molar mass, M	28 g mol ⁻¹	-	
Quartz	Wavelength range	0.3-1 μ m 1-2 μ m 2-4 μ m 4-6 μ m 6-8 μ m		
	Refractive index	1.46 1.45 1.42 1.33 1.12	$0.3 < \lambda < 8$ μ m	[7]
	Absorption coefficient	5.1 1.0 45.4 7224.1 50268.5	$0.3 < \lambda < 8$ μ m	[6]
	Density, ρ	2649 kg m ⁻³	-	[6]
	Specific heat capacity, C_p	$859.05 + 0.3 \times T$ JK ⁻¹ kg ⁻¹	$700 < T < 1300$ K	[8]
	Thermal conductivity, k	$0.96 + \frac{2.43 \times 10^{-3} \times T}{7.94 \times 10^{-10} \times T^3}$ W m ⁻¹ K ⁻¹ - $2.29 \times 10^{-6} \times T^2$ +	-	[6]
Tungsten	Density, ρ	19300 kg m ⁻³	-	[6]
	Resistivity, r	$5.92 \times 10^{-11} \times T^{1.2036}$	$300 < T < 3655$ K	[8]
	Emissivity, ε	2D interpolation from experimental data $< 4\mu$ m; Drude's formula $> 4\mu$ m	$1200 < T < 3200$ K	[9]
	Thermal conductivity, k	$3.3 \times 10^{-5} \times T - 0.1144 \times T + 199.7$ W m ⁻¹ K ⁻¹	-	[6]

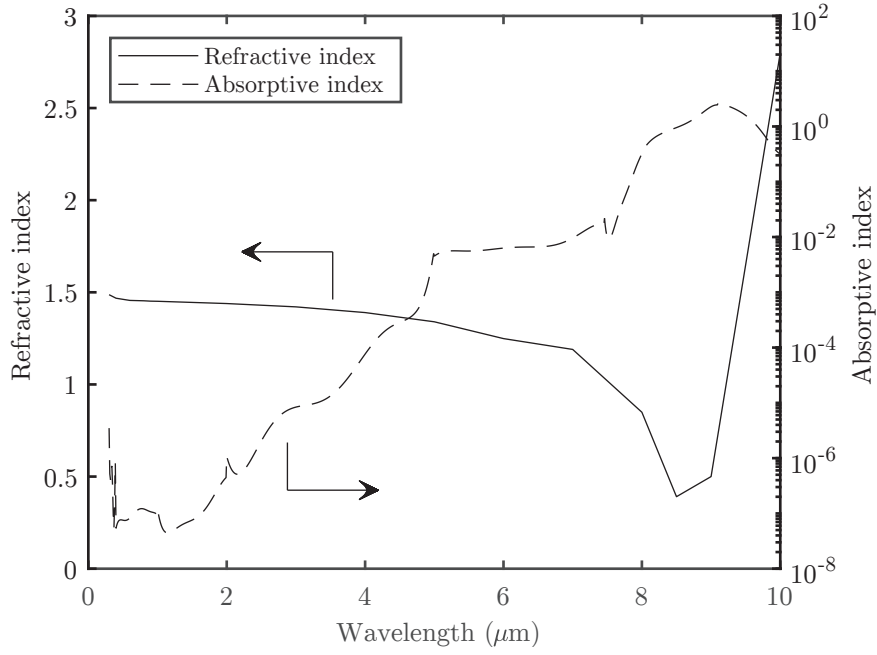


Figure C.2: Refractive index and absorption index of quartz [7].

The bulk absorption data used in this work is compared to the data compiled by *Kitamura et al.* [7] in Fig. C.3.

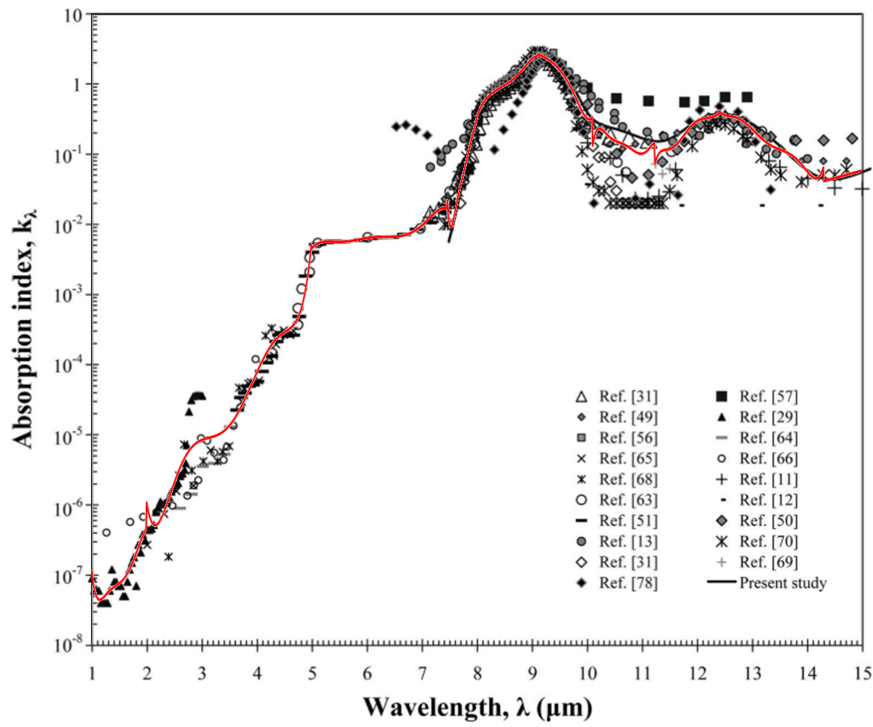


Figure C.3: Quartz absorption data from several sources compiled by *Kitamura et al.* [7] with an overall of the piecewise polynomial fit of this data by Mecit [10] in red.

The efficiency maps for the optimisation of the ellipses is for the three sources studies in this work are presented in Fig. C.4. These maps were calculated by searching a range of suitable ellipse sizes while maintaining the geometric centre of the filament at the focal point of the generated ellipses. The inlet orifice size was set as the diameter of the quartz envelope plus a 1 mm gap to account for tolerances.

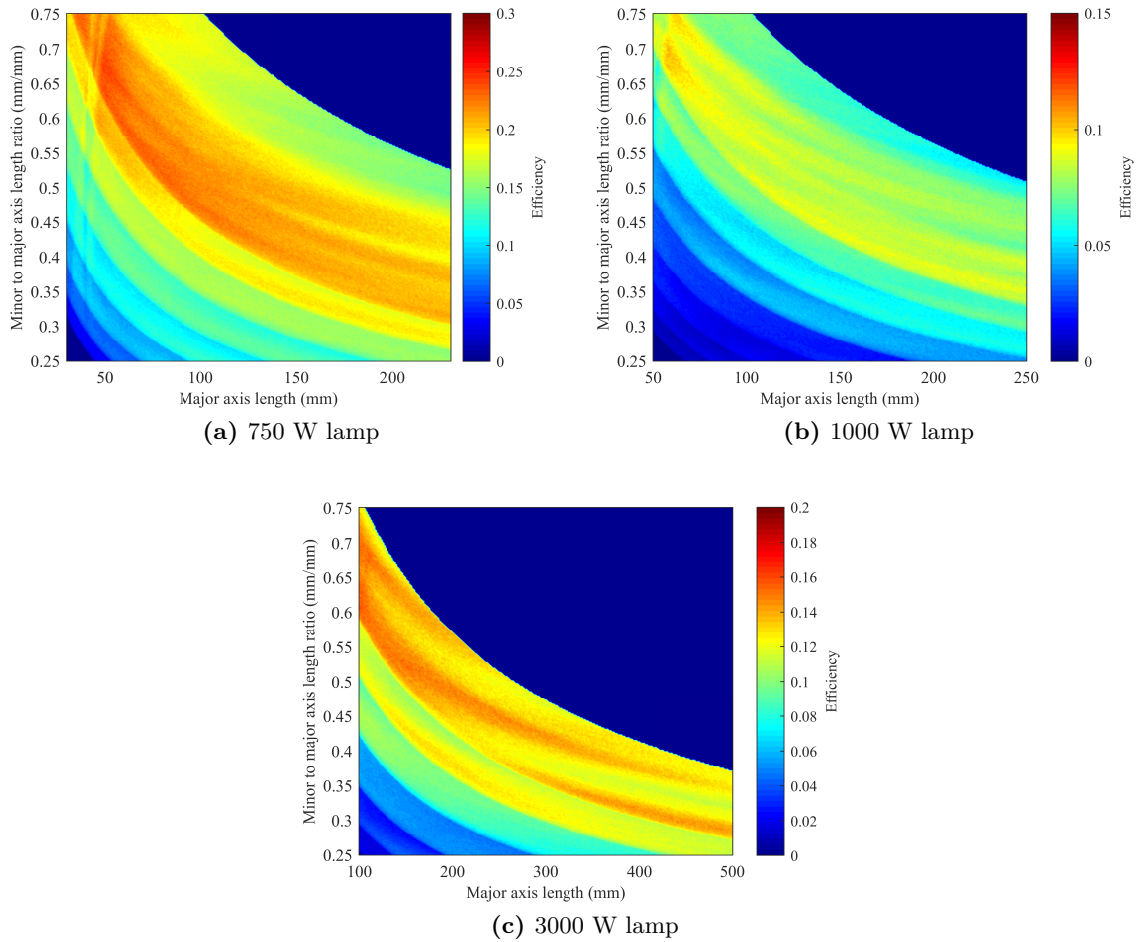


Figure C.4: Ellipse efficiency maps for the various sources determined using the 3D model.

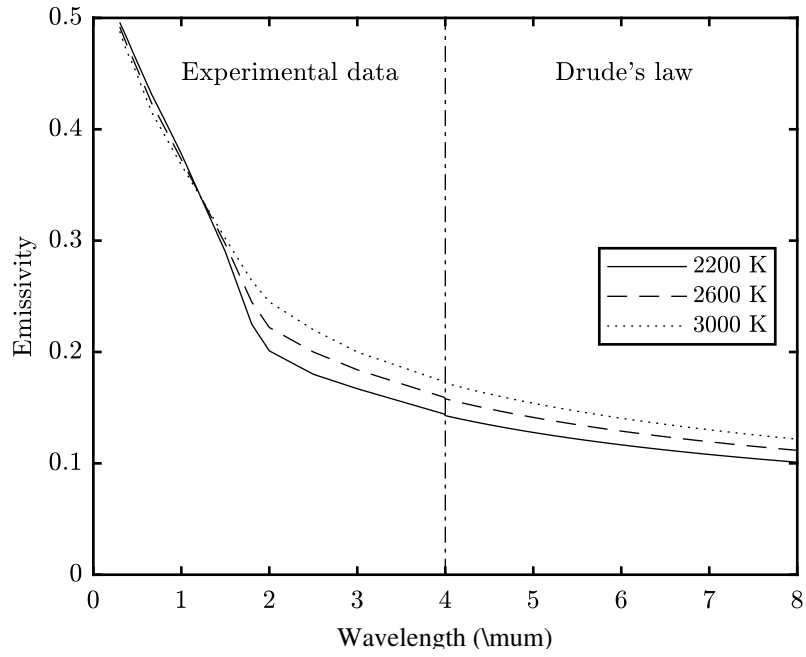


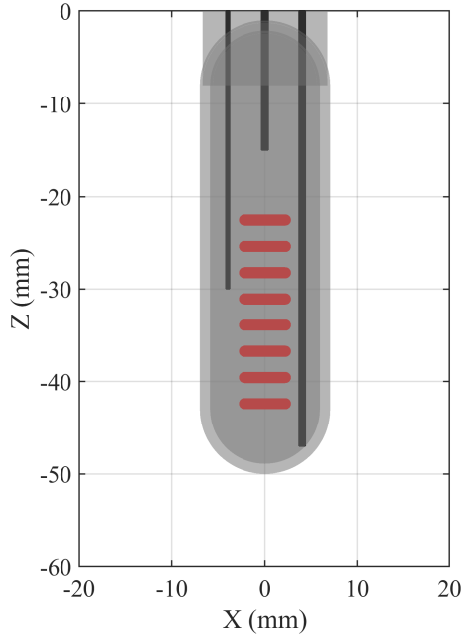
Figure C.5: Emissivity of tungsten using data from Forsythe and Adams [9] and Drude's formula.

The ANOVA table generated from the optimisation of the genetic algorithm is presented in Table C.2.

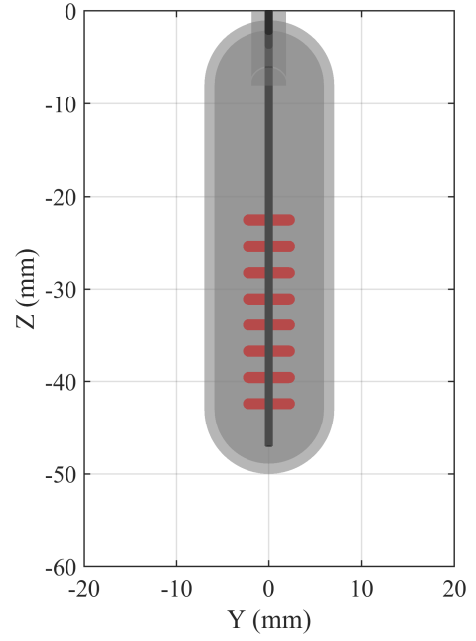
Table C.2: ANOVA table.

Source	DOF	SEq. SS	Adj. SS	Adj. MS	F	P
Migration direction	1	0.000029	0.000029	0.000029	0.75	0.399
Fitness scaling function	3	0.000105	0.000105	0.000035	0.91	0.461
Selection function	3	0.000023	0.000023	0.000008	0.2	0.897
Elite count	3	0.000316	0.000316	0.000105	2.74	0.08
Crossover fraction	3	0.000187	0.000187	0.000062	1.62	0.227
Crossover function	3	0.000778	0.000778	0.000259	6.73	0.004
Residual Error	15	0.000578	0.000578	0.000039		
Total	31	0.002016				

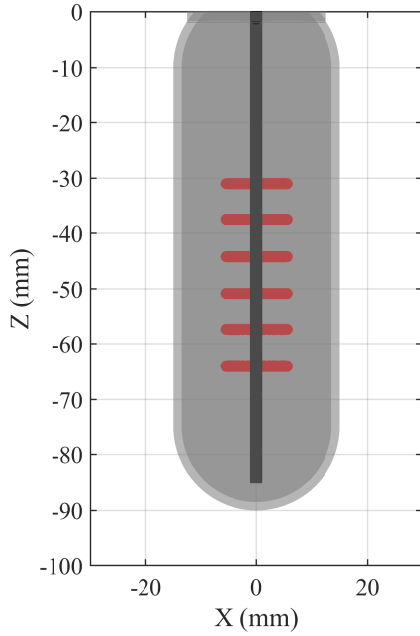
The 750 W and 3000 W lamp schematics are shown in Fig. C.6



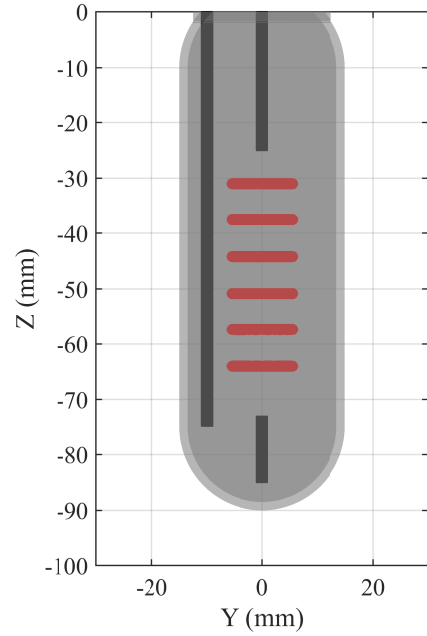
(a) 750 W XZ-plane view.



(b) 750 W YZ-plane view.



(c) 3000 W XZ plane view.



(d) 3000 W YZ plane view.

Figure C.6: Schematic of the 750W and 3000 W lamps

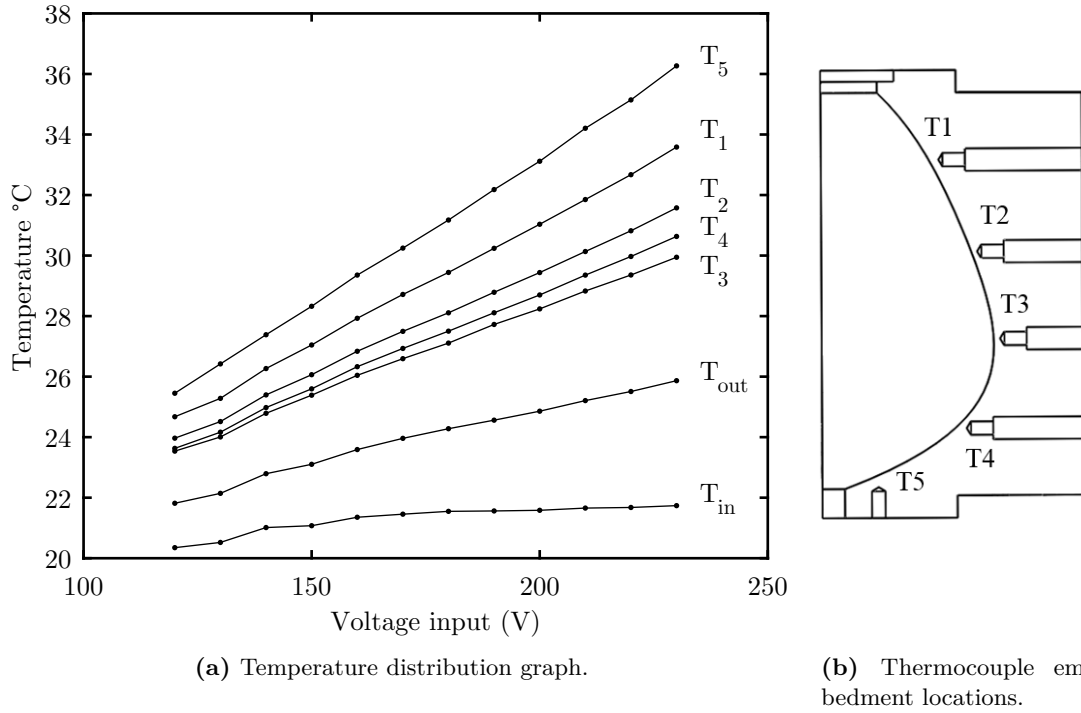


Figure C.7: Temperature distribution in the Au-coated FIRH across a range of input voltages. Coolant flow rate set to 2 litres per minute at 21°C and compressed air cooling to 1 bar. The coolant flow temperature (T_{in} and T_{out}) are also included in the figure.

C.2 Calibration of the power meter

The power meter used throughout this study needs to be validated to ensure that there are no significant errors in the measurement. This can be achieved by developing a radiation heat flux sensor for which the uncertainty has been quantified to a high degree of accuracy. The device developed is shown in Fig. C.8, which consists of a sensing surface which is coated with an absorbing paint, three thermocouples which are 15 mm apart, and a heat sink in the form of liquid cooled channels. The block was approximately 20×20 mm in cross-sectional area.

An uncertainty analysis for the heat flux sensor can be carried out based on a MC technique for heat flux sensors proposed by Kempers and Robinson [11] and used in the previous work of the author [12]. The thermocouples were calibrated against a high precision PRT Probe with steps of 20°C resulting in uncertainties of $\pm 0.1^\circ$ across the test range (20°C to 60°C). The position of the thermocouples was measured using an optical microscope with a resolution of 1 micron. For the thermocouples in the neck of the copper block, the distance between the two thermocouples is the critical value and was measured as the distance from

the top edge to top edge of the thermocouple wells. This process was repeated ten times and the two standard deviations of the resulting values provided the uncertainties for the distance between thermocouples. The distance between thermocouples was found to be 15 mm $\pm$ 0.02 mm. The uncertainty associated with the absorbing surface must also be taken into account which is assumed to be $\pm$ 0.7% for the spectrally averaged absorptivity of the data shown in Fig. C.9 [1]. This delivers a total uncertainty of $\sim$ 5% at 30 W of incident power and $<$ 2% at incident power levels of 120 W. Good agreement is shown between the calibrated sensor and the commercial power meter.

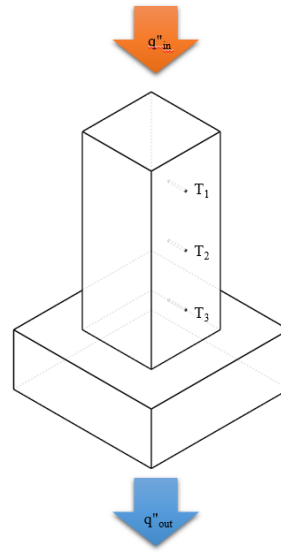
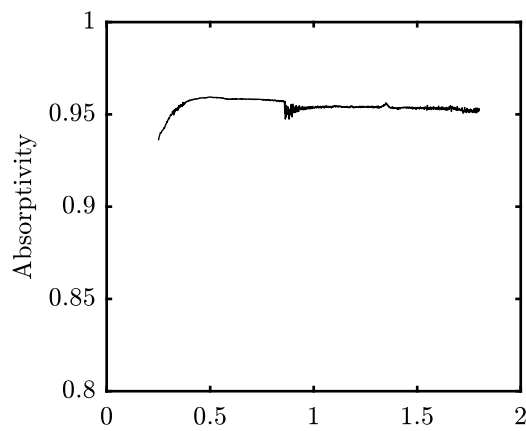
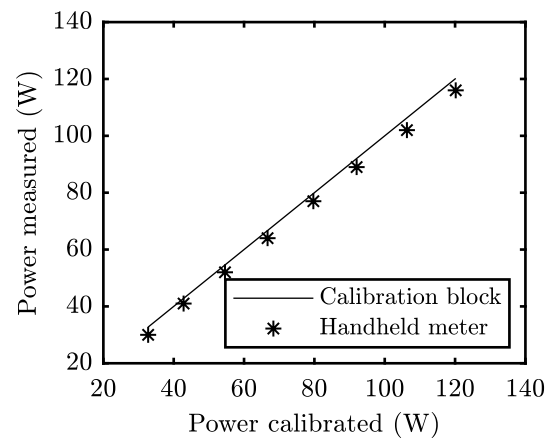


Figure C.8: Copper heater block isometric view.



(a) Absorptivity of the black copper surfaces



(b) Comparison between the handheld power meter and heat flux sensor

Figure C.9: Calibration of hand held power meter using radiation heat flux meter.

C.3 Ray tracing algorithms

C.3.1 Ellipse intersection code

The ellipse will be defined directly using the Cartesian based equation:

$$\left(\frac{x - x_0}{a}\right)^2 - \left(\frac{y - y_0}{b}\right)^2 = 1 \quad (\text{C.1})$$

Where a and b are the minor and major axis lengths respectively, and x_0 and y_0 is the coordinates of the centre point of the ellipse. In this work, the equation can be simplified, as the ellipse is located on the origin. The equation of a ray in vector format is presented in Eq. 5.21 on page 125 which can be rearranged to remove the parametric variable t , and isolated to find x :

$$t = \frac{x - x_1}{V_x} = \frac{y - y_1}{V_y} \quad (\text{C.2})$$

$$x = x_1 + (y - y_1) \frac{V_x}{V_y} \quad (\text{C.3})$$

This solution for x can be substituted into the equation of an ellipse, rearranged, and solved for y :

$$y = \frac{-b^2 v_x y_1 + b^2 v_x v_y x_1 \pm \sqrt{a^2 b^2 v_y^2 (a^2 v_y^2 + b^2 v_x^2 - (v_y x_1 - v_x y_1)^2)}}{a^2 v_y^2 + b^2 v_x^2} \quad (\text{C.4})$$

Which provides two y -solutions, one of which will be at the current ray location in the case of the ray being reflected on the ellipse. The final solution can be determined by selecting the solution with the largest value of the parametric value of t in the vector line equation. The normal vector at the intersection location can be found by the following equation:

$$n = \left[-x \frac{b}{a}, -y \frac{a}{b}\right] \quad (\text{C.5})$$

The new vector direction can be found using Eq. 5.18 for specular or by a Lambertian distribution for diffuse reflections, as before.

C.3.2 Coiled-coil ray tracing algorithm

In order to characterise the rate of light recycling of the filament, the filament geometry needs to be modelled in its entirety. The equation of a coiled-coil is provided by Winslow

[13]. This equation can be used to determine the path of the filament wire based on a major radius, minor radius, height of a single turn of the major coil, number of turns of the major coil, and number of turns of the minor coil for each turn of the major. These parameters are provided in Table C.3 for the 750 W and 1000 W lamp. The diameter and surface area of the filament can be found using the methods outlined in section 3.2.3. The major radius (R) and the minor radius (r) can be calculated by measuring the filament with a calliper while accounting for the radius of the filament (r_{fil}). The number turns of the large coil is apparent under visual inspection and the number of turns of the smaller coil can be determined by matching the area of the filament to that calculated in section 3.2.3. The area of the filament was calculated by modelling the structure in SolidWorks with the parameters given in Table C.3 and then using the measure tool to determine the area. The number of turns of the small coil was adjusted to match the area of the filament to the measured value.

Table C.3: The geometry of the coiled coils for the 750 W and 1000 W lamps.

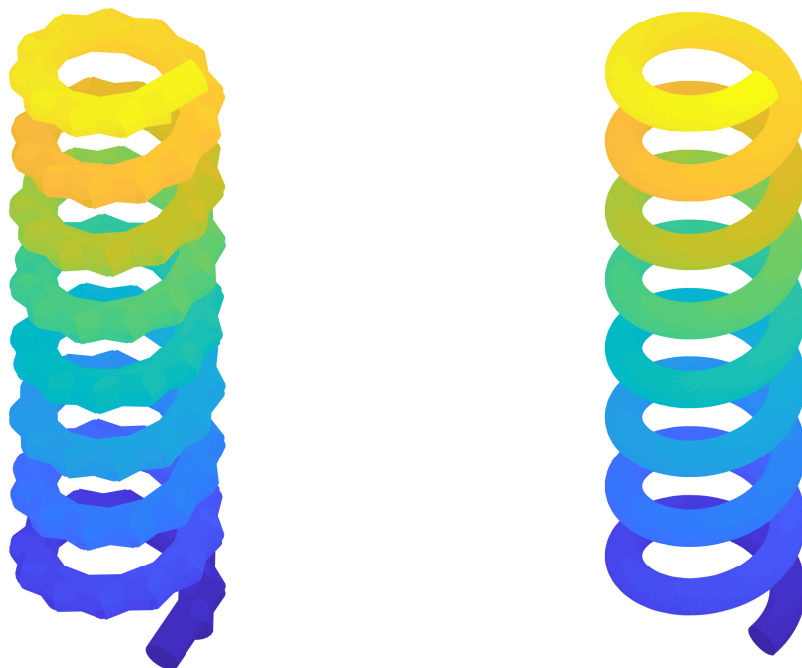
Lamp	$h_{coil}(mm)$	R (mm)	r (mm)	$r_{fil}(mm)$	N	n
750 W	2.27	2.3	0.489	0.111	8	43.6
1000 W	3.25	2.9	0.51	0.09	8	66.8

The filament surface can then be modelled by dividing the filament's coiled-coil path into a number of lengths. Each of these lengths is then assumed straight and can be represented using a cylinder section with its centre location on the path of the length. With sufficiently small divisions, the filament can be accurately represented as shown in Fig C.10b and c.

Once the orientation of the cylinders are known, a rotation matrix can be used to rotate the cylinder into a vertical position. The same rotation matrix is then applied to a ray which can potentially intersect the filament and after which, a 2D intersection tests are carried out using a similar method to Fig. 7.6 on page 171. If an intersection is found to occur in the rotated condition, the actual intersection can be found by applying the inverse of the rotation matrix. This process is repeated for each cylinder that composes the filament structure.

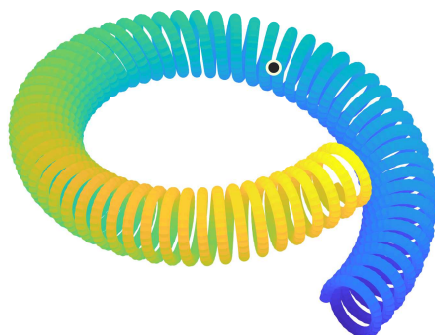
There are a number of noteworthy points about this method:

1. A large number of cylinders are required to model the filament accurately. This is even more so the case when the double coiled filament is modelled. To determine the light recycling factors, 10,000 divisions of the filament were used for both the 750 W and



(a) Low resolution single-coil filament using 100 divisions

(b) High resolution single-coil filament using 1000 divisions



(c) High resolution section of a double-coil filament using 2000 divisions

Figure C.10: Filament discretisation using cylindrical elements.

1000 W sources.

2. As a result of the large number of solids to be traced, this algorithm is computationally expensive. This algorithm is over an order of magnitude slower than the standard 3D ray tracer developed in Chapter 7 and thus, this cannot be used during an optimisation process.
3. Since the radius on the outer turn of the coil is larger than the path of the filament, the

length of each cylinder must be increased to ensure that full coverage of the filament is achieved. The increase in the length of the cylinders can be determined using $(r_{fil} + r)/r$.

Points can be seeded on the surface of the filament using a random position along the length of the filament path and then a random angle to allow the position on the surface to be selected. Similar to the case of a torus (see section 7.2.3.1), some rays must be rejected on the inside curve surface of the filament to ensure that an even distribution on the surface. This is particularly important as the local light recycling rate is heavily influenced by the seed position.

To validate the algorithm, it was compared to the commercial ray tracing software package TracePro using a number of a double-coil filament geometry configurations. These results are summarised in Table E2 showing good agreement over a range of filament geometries pertinent to this study.

Table C.4: Comparison of the coiled-coil ray tracing algorithm to TracePro using 10000 rays.

Configuration	1	2	3	4
r_{fil}	0.105	0.105	0.105	0.105
r	0.5	0.5	0.5	0.5
R	2.2	2.2	2.2	5
N	1	1	1	1
n	15	30	45	45
h	2.625	2.625	2.625	2.625
TracePro LR rate	0.175	0.357	0.477	0.249
Matlab LR rate	0.177	0.351	0.489	0.262
Difference	1.4%	1.8%	2.5%	4.9%

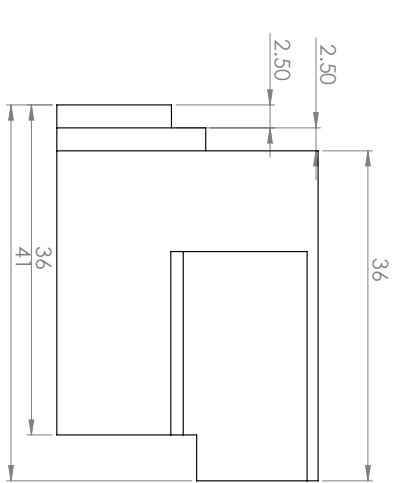
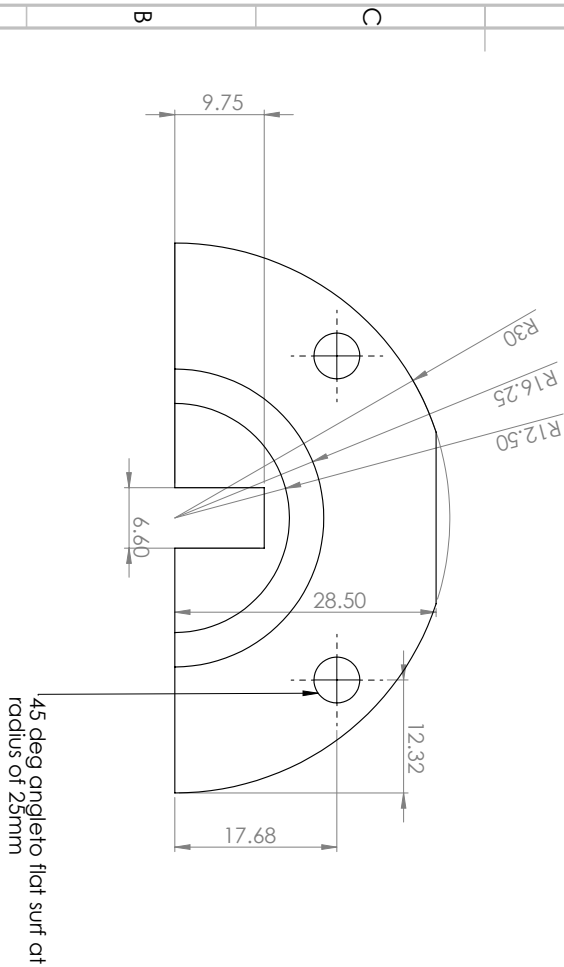
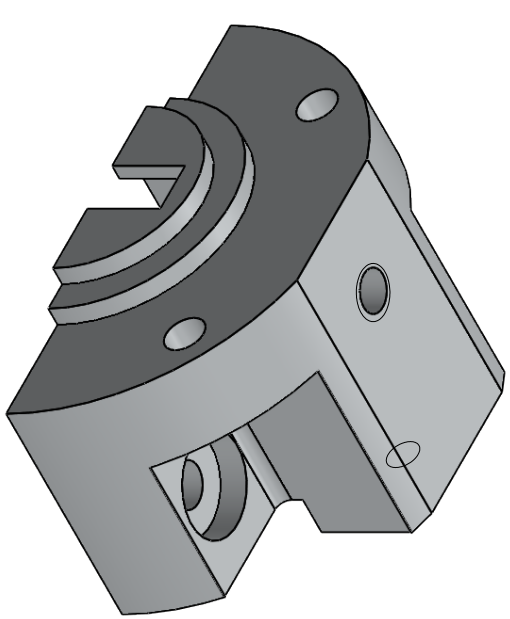
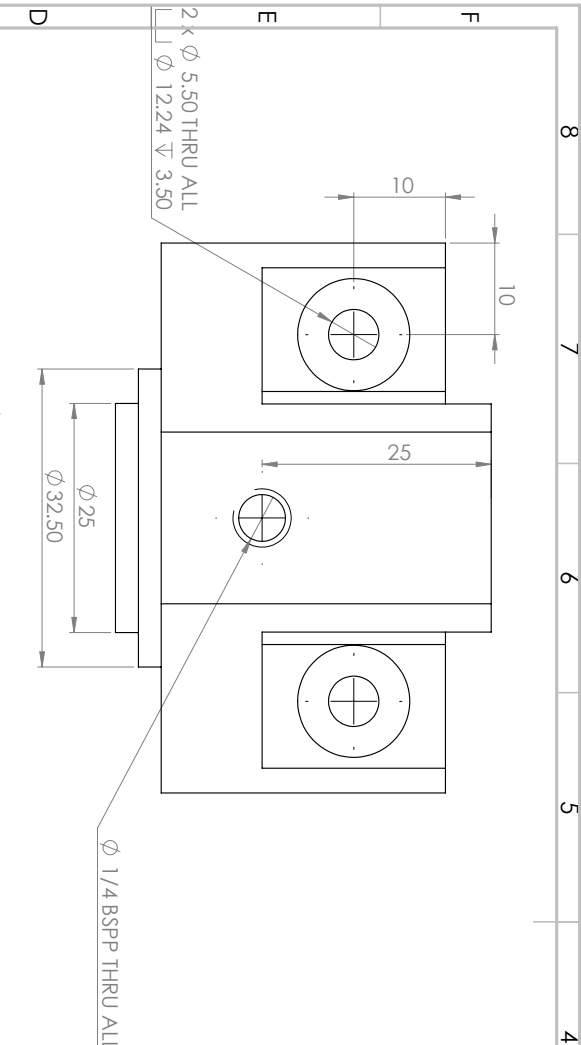
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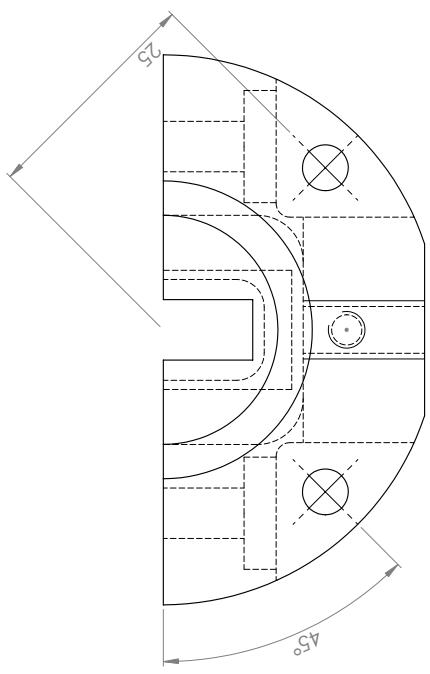
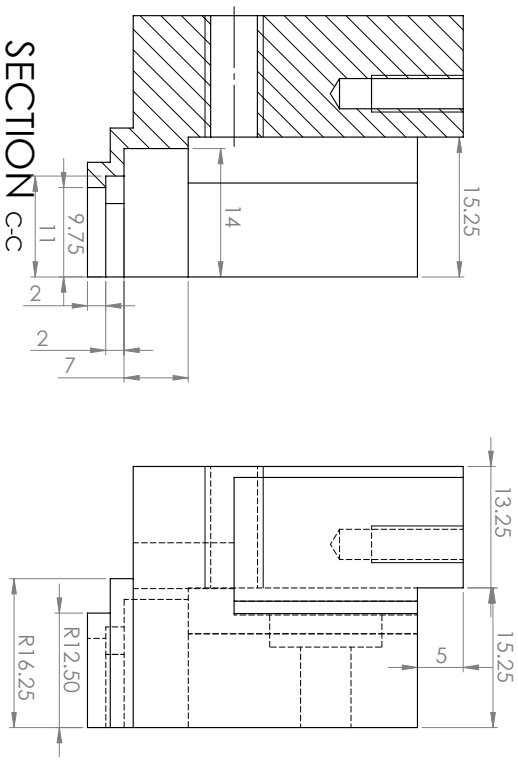
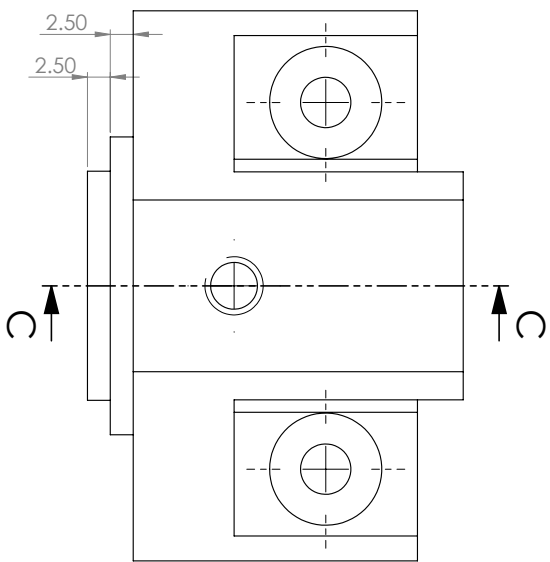
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Appendix D

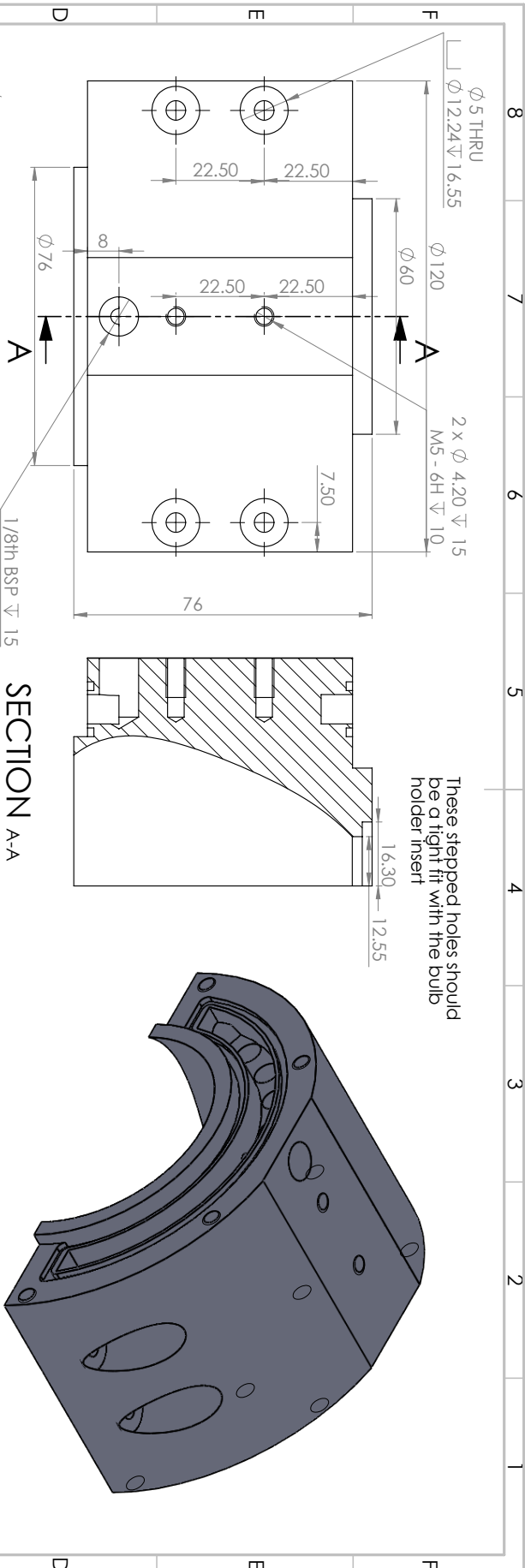
Engineering drawings



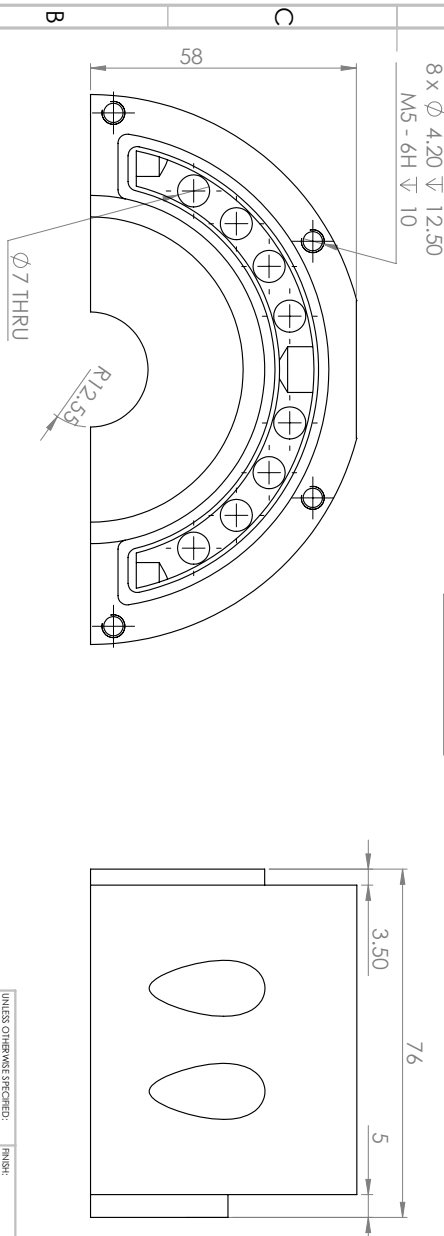
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SECTION A-A



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