Facade Integrated Concrete Solar Collectors

By

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A thesis submitted for the degree of Doctor of Philosophy to the University of Dublin, Trinity College.

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Declaration

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________________________
Richard O’Hegarty
Abstract
Concrete solar collectors are a type of solar thermal collector that are formed by embedding pipes within a layer of concrete that acts as the solar energy absorber. Concrete is a cheap, durable and abundant material that can replace the metal or plastic absorbers of classical solar collectors. Concrete solar collectors also offer a unique façade integrated solar thermal solution, allowing for seamless integration with precast concrete cladding systems. Past research of non-integrated, roof-attached, concrete solar collectors have largely focused on one-off experimental studies in high temperature climates. This research (1) experimentally investigates the performance of a façade integrated concrete solar collector in a mid-latitude European climate (Dublin) (2) develops and validates a 3D numerical model which is used to predict the performance of other façade integrated concrete solar collectors in other European climates and (3) conducts an in-depth parametric investigation of the concrete solar collector using a simplified 2D numerical model. The experimental work tests a real scenario, models are then validated by these results and used to consider other climates (in 3D) and to carry out a parametric investigation (in 2D).

The experimental set-up of the concrete solar collector is designed to represent a south facing façade installation. The experimental results showed that approximately one quarter of the annual hot water demand of a single occupant dwelling could be provided using 1m² of concrete solar collectors with spring and autumn months producing the highest daily energy outputs; attributed to the vertical orientation of the concrete solar collectors. A validated 3D numerical model is developed and used to expand the study to different collectors and systems, as well as three additional, contrasting, Northern and Southern European climates (Helsinki, Sofia and Seville). Annual solar fractions (proportion of the energy required for hot water preparation that is provided by the solar collector) of approximately 20% (Helsinki), 25% (Dublin), 29% (Sofia) and 51% (Seville) are predicted for a small apartment building using a façade integrated concrete solar collector. The thermal energy output of a concrete solar collector is dictated by its material (e.g. thermal conductivity of concrete and pipe), geometry (e.g. pipe spacing, pipe diameter, collector thickness, pipe embedment depth) surface finish (e.g. absorptance) and fluid flow (e.g. mass flow rate). Given the wide range of individual parameter values documented in the literature, an in-depth investigation into these parameters is evidently required. An experimentally validated 2D numerical model is subsequently developed to conduct the computationally intensive parametric investigation. Parameters are investigated individually and compared collectively within the range of values found in the literature. Concrete conductivity and solar absorptance, along with pipe embedment depth and spacing are identified as key performance parameters. These material and geometric parameters are limited by practical, economic and aesthetic constraints which are also examined and summarised. Furthermore, concrete solar collector’s efficiency (56% on a sample clear day) compare well with other unglazed collectors (metallic absorber; daily efficiency on the same day = 62%; polymer absorber; daily efficiency on the same day = 29%).
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List of Acronyms

BIPV  Building Integrated Photovoltaic
BIST  Building Integrated Solar Thermal
CFD  Computational Fluid Dynamics
CSC  Concrete Solar Collector
DHW  Domestic Hot Water
ETC  Evacuated Tube Collector
FE  Finite Element
FEA  Finite Element Analysis
FEM  Finite Element Method
FIST  Facade Integrated Solar Thermal
FPC  Flat Plate Collector
HVAC  Heating Ventilation and Air Conditioning
HWB  Hottel Whillier Bliss
HWC  Hot Water Consumption
Lcd  Litres per capita per day
MSTC  Massive Solar Thermal Collector
NSAI  National Standards Authority of Ireland
PEX  Cross-linked Polyethylene
PMAE  Percentage Mean Absolute Error
PTSFC  Partially-Transparent Solar Facade Collector
SF  Solar Fraction
SH  Space Heating
STC  Solar Thermal Collector
STF  Solar Thermal Façade
UC  Unglazed Collector
Nomenclature

\( A_c \) = Collector area (m\(^2\))

\( A_p \) = Pipe cross-sectional area (m\(^2\))

\( A_p \) = The area of the wetted surface of the pipe (m\(^2\))

\( C_{sys} \) = Capital cost of system (€)

\( C_{exp} \) = Capital cost of experimental system using (€)

\( C_{BL, bespoke} \) = Capital cost of building-integrated system using bespoke material costs (€)

\( C_{BL, bulk} \) = Capital cost of building-integrated system using bulk material costs (€)

\( C_{SA, bespoke} \) = Capital cost of stand-alone system using bespoke material costs (€)

\( C_{SA, bulk} \) = Capital cost of stand-alone system using bulk material costs (€)

\( c_c \) = Specific heat capacity of concrete (J/kg.K)

\( c_f \) = Specific heat capacity of a fluid (J/kg.K)

\( C_l_{cov} \) = Cloud cover (Oktas)

\( c_w \) = Specific heat capacity of water (J/kg.K)

\( D_{emb} \) = Pipe embedment depth (m)

\( D_i \) = Pipe diameter (m)

\( D_s \) = Pipe spacing (m)

\( f \) = Darcy Welsbach friction factor

\( f_{cloud} \) = Cloud sky fraction

\( Fr \) = Heat removal factor

\( g \) = Gravity (m/s\(^2\))

\( G \) = Shortwave radiation incident on the collector (W)

\( Gr \) = Grashof’s number

\( h_f \) = Heat transfer coefficient between fluid and pipe (W/m\(^2\))
\( h_t \) = Head loss due to frictional and local losses (W/m^2)

\( h_{nat} \) = Natural convective heat transfer coefficient (W/m^2)

\( h_{wind} \) = Forced convective heat transfer coefficient due to wind (W/m^2)

\( I_d \) = Daily solar radiation (kWh)

\( i_f \) = Inflation rate (%)

\( I_s \) = Solar irradiance (W/m^2)

\( I_{ave} \) = Average solar irradiance (W/m^2)

\( I_s(\lambda) \) = Wavelength specific solar irradiance (W/m^2)

\( k_c \) = Concrete conductivity (W/mK)

\( k_i \) = Insulation conductivity (W/m.K)

\( k_p \) = Pipe thermal conductivity (W/mK)

\( k_w \) = Water thermal conductivity (W/m.K)

\( L \) = Characteristic length (m)

\( \dot{m} \) = Mass flow rate (kg/s)

\( M_{load} \) = Hot water load rate (kg/s)

\( m_{tank} \) = Mass of water in the storage tank (kg)

\( N \) = Number of occupants

\( P \) = Pressure (Pa)

\( P_h \) = Hydraulic pump power (W)

\( P_{ms} \) = Motor pump power (W)

\( P_P \) = Payback period (years)

\( Pr \) = Prandtl’s number

\( Q_r \) = Useful energy gains (kWh)

\( Q_l \) = Useful energy losses (kWh)
\( Q_s \) = Stored energy (kWh)

\( Q_u \) = Useful energy output (kWh)

\( Q_{u,d} \) = Useful energy output per day (kWh)

\( Q_{u,sys} \) = Useful energy output per day from the system (kWh)

\( Q_{\text{aux}} \) = Rate of energy load from an auxillary source (W)

\( Q_{c,f} \) = Forced convection heat loss from the wind (W)

\( Q_{c,n} \) = Natural convective heat loss from the surrounding air (W)

\( Q_{\text{fluid}} \) = Heat flux from pipe to fluid (W)

\( Q_{\text{flux}} \) = Heat flux (W)

\( Q_{\text{loss}} \) = Rate of energy loss (W)

\( Q_{r,l} \) = Diffuse longwave radiation to the sky and the surroundings (W)

\( Q_{s,\text{load}} \) = Energy load from solar source (W)

\( Q_u^+ \) = Positive useful energy output (W)

\( Q_u^- \) = Rate of useful energy output (W)

\( Q_{\text{wall}} \) = Heat flux to fluid (W)

\( R (\lambda) \) = Wavelength specific reflectivity

\( R \) = Reflectivity

Ra = Rayleigh’s number

\( R_e \) = Reynolds number

\( RH \) = Relative humidity (%)

\( R_{\text{std}} (\lambda) \) = Wavelength specific reflectivity of a standard surface

\( S \) = Annual revenue savings (€)

\( SPPp \) = Simple payback period (years)
\( S_{\text{Dart}}(\lambda) = \) Integrated sphere dark photon reading

\( S_{\lambda} = \) Integrated sphere sample photon reading

\( S_{\text{std}}(\lambda) = \) Integrated sphere standard photon reading

\( T_{\text{fluid,wall}} = \) Temperature of fluid contacting pipe (K)

\( T = \) Temperature (K)

\( T_{\text{a}} = \) Ambient temperature (K)

\( T_{\text{a,in}} = \) Indoor ambient temperature (K)

\( T_{\text{app}} = \) Application temperature (K)

\( T_{\text{cold}} = \) Cold side temperature of concrete (K)

\( T_{\text{dp}} = \) Dew point temperature (K)

\( T_{\text{f,av}} = \) Average fluid temperature (K)

\( T_{\text{f,wall}} = \) Fluid wall temperature (K)

\( T_{\text{hot}} = \) Hot side temperature of concrete (K)

\( T_{\text{in}} = \) Inlet fluid temperature (K)

\( T_{\text{main}} = \) Mains water temperature (K)

\( T_{\text{o}} = \) Outlet fluid temperature (K)

\( T_{\text{pipe,wall}} = \) Temperature of pipe contacting the internal fluid (K)

\( T_{\text{p,wall}} = \) Pipe wall temperature (K)

\( T_{\text{sky}} = \) Sky temperature (K)

\( T_{\text{surf}} = \) Sky temperature (K)

\( T_{\text{tank}} = \) Tank temperature (K)

\( T_{\text{tank,ave}} = \) Average tank temperature throughout the day (K)

\( T_{\text{tank,max}} = \) Maximum tank temperature (K)

\( T_{\text{tank,min}} = \) Minimum tank temperature of the previous morning (K)
\( T_{w,av} = \) Average wall temperature (K)
\( T_{w,in} = \) Indoor wall temperature (K)
\( t_{\text{slice}} = \) Thickness of concrete sample (m)
\( u_f = \) Fluid velocity (m/s)
\( u_{\text{fluid,wall}} = \) Fluid velocity at point of contact with pipe (m/s)
\( U_l = \) Total thermal transmittance (W/m\(^2\)K)
\( u_w = \) Wind speed (m/s)
\( \dot{V} = \) Volumetric flow rate (m\(^3\)/s)
\( z = \) Elevation (m)
\( \alpha = \) Absorptance
\( \alpha_r = \) Solar absorptance
\( \beta = \) Thermal expansion of a fluid (1/K)
\( \delta = \) Concrete solar collector thickness (m)
\( \Delta L = \) Pipe length (m)
\( \Delta T = \) Temperature difference (K)
\( \Delta t_{\text{step}} = \) Time step (s)
\( \nabla = \) Symbol for the spatial vector partial derivative
\( \varepsilon = \) Thermal emissivity
\( \varepsilon_{\text{clear sky}} = \) Clear sky emissivity
\( \varepsilon_{\text{sky}} = \) Sky emissivity
\( \eta_{\text{aux}} = \) Auxiliary heater efficiency (%)
\( \eta_d = \) Daily efficiency (%)
\( \eta_m = \) Motor efficiency (%)
\( \eta_p = \) Pump efficiency (%)
\( \kappa \) = Local friction loss coefficients

\( \mu \) = Dynamic viscosity (Pa.s)

\( \rho_c \) = Concrete density (kg/m\(^3\))

\( \rho_w \) = Density of water (kg/m\(^3\))

\( \sigma \) = Stefan Boltzmann constant (W/m\(^2\)K\(^4\))

\( (ra) \) = Transmittance-absorptance produce
Chapter 1

Introduction
1 Introduction

1.1 Background

Buildings account for over one third of final energy consumption worldwide, with space heating, cooling and domestic hot water accounting for over half of the building’s energy needs (IEA, 2013). These energy requirements are typically provided by burning depleting fossil fuel resources which pollute the environment and accelerate global warming. The sun offers an environmentally clean and renewable energy source. Energy from the sun can be efficiently harnessed by solar thermal technologies to provide for a building’s thermal energy needs.

Solar thermal technologies harness solar energy and convert it into useful heat. To date the global installed solar thermal capacity has increased annually since 2000 and by the end of 2016 a total cumulative installed capacity of 456 Giga Watts (= 652 million m$^2$) was documented, second only to wind energy when compared with other modern renewable technologies (Weiss et al., 2017). These solar thermal technologies vary in complexity depending on the required application temperature. For buildings, solar thermal technologies achieve temperatures that coincide with the thermal requirements of the building, e.g. 40°C for underfloor heating or approximately 55°C for domestic hot water. Solar thermal technologies used in building applications are often referred to as Solar Thermal Collectors (STCs). These STCs consist of a solar absorber which is typically made from a conductive metal with a dark coating. A network of pipes, or channels, is used to extract the heat from the absorber. Glazing and insulation can also be used to reduce heat losses from the absorber to the surrounding environment.

Traditionally, STCs are mounted on frames that are attached to the roofs of buildings. Much contemporary research is focused on integrating the STCs into the building’s architecture (Buker & Riffat, 2015; O’Hegarty et al., 2016; Zhang et al., 2015). Integrating STCs into the building skin can offset other facade cladding materials (Norton et al., 2011). A façade integrated STC, or a Solar Thermal Façade (STF), is particularly worthwhile in buildings with limited roof space and demanding hot water loads, such as in high rise apartment blocks, hotels and hospitals (Chow et al., 2006; Chow et al., 2005; O’Hegarty et al., 2015; Shi et al., 2013). Additionally, other components of building services compete for the valuable roof space. STFs replace building cladding elements and their associated embodied energy (Greening & Azapagic, 2014; Lamnatou et al., 2015; Maurer et al., 2015a). However, vertically orientating the STCs reduces the annual solar yield per m$^2$ of collector (by approximately 26% in Dublin) when compared with an optimally tilted surface as is displayed in Figure 1.1.
Preserving the architectural aesthetic is a concern when it comes to the building integration of STCs. It is important that the integration of solar thermal collectors does not negatively affect the building’s architecture, particularly if the building integrated solar thermal market is to expand sufficiently (Munari Probst & Roecker, 2007; Probst & Roecker, 2012). Two approaches are typical for building integration:

1) The STC is first specified and the façade is designed to match that STC. This approach allows greatest flexibility for the designers of the solar thermal collector but compromises the freedom of the architects and building designers when trying to integrate these as a façade element.

2) Typical façade typologies are identified and a specific solar thermal solution is provided for each. There is a significant amount of research on providing a range of colour options to mimic metallic cladding systems (Anderson et al., 2010; Dudita et al., 2014; Kalogirou et al., 2005; Mertin et al., 2013), however a lack of research exists for building integrated solutions for other façade types such as timber or concrete. This research focuses on Concrete Solar Collectors (CSCs), a building integrated solution for precast concrete cladding systems.

CSCs offer a unique solution for the building integrated solar thermal market, but have not been investigated to the same level of detail as other building integrated STCs such as the standard flat plate collectors or evacuated tube collectors (O’Hegarty et al., 2016).

Typically, the efficiency of solar thermal technologies is evaluated using instantaneous measurements. The non-negligible thermal mass of CSCs means that typical instantaneous Hottel-Whillier-Bliss (HWB) models are not appropriate for CSC analysis. The HWB model consists of a set of equations which are commonly used to model the performance of flat plate solar collectors (Duffie & Beckman, 2013).
A number of 1D (D’Antoni & Saro, 2013; Sarachitti et al., 2011; Tanzer & Schweigler, 2016) and 2D (Abbott & Ellis, 2007; Bopshetty et al., 1992; Sokolov & Reshef, 1992) models have been developed, which do account for these storage effects, however, the entire 3D geometry of the CSC is not captured in 1D and 2D models. CSCs have also been modelled successfully as part of novel solar thermal systems (Blecich & Orlić, 2012; D’Antoni & Saro, 2013; Tanzer & Schweigler, 2016). To date there is a paucity of detailed 3D models of CSCs.

Real time experimental studies of CSCs are so far limited to roof mounted/integrated systems in extreme high temperature climates such as India (Chaurasia, 2000; Krishnavel et al., 2014; Nayak et al., 1989; Patil et al., 2016), Tunisia (Hazami et al., 2010; Hazami et al., 2005), Jordan (Al-Saad et al., 1994) and Thailand (Sarachitti et al., 2011). Unlike standard solar thermal technologies, which are defined by an instantaneous efficiency curve, a common performance indicator has not been established for CSCs. Some studies refer to the maximum outlet fluid temperature, with values varying between 33 °C and 65 °C (Chaurasia, 2000; Hazami et al., 2005; Keste & Patil, 2012; Krishnavel et al., 2014; Kumar et al., 1981). Other studies refer to the daily efficiency, with values ranging from 28% to 40% (Al-Saad et al., 1994; Hazami et al., 2010; Kumar et al., 1981; Nayak et al., 1989). This study investigates the performance of a vertically installed CSC in Dublin (Ireland) and refers to both performance indicators (maximum outlet temperature and daily efficiency); in addition, it refers to the Solar Fraction (SF) i.e. the proportion of thermal energy for Domestic Hot Water (DHW) provided by the CSCs.

1.2 Research objectives

The aim of this research is to investigate Concrete Solar Collector (CSC) technology for building facade integration, to assess its suitability in a European climate and to evaluate its ability to reduce the thermal energy demand of buildings.

To successfully answer this research question, this thesis addresses the following core objectives:

1) To present a comprehensive literature review of building integrated solar thermal solutions and concrete solar collectors.

   - To investigate the research surrounding building integrated solar thermal technologies and to categorise these by their component make-up and technology type.
   - To identify the potential for CSCs amongst the range of solar thermal technologies and to identify gaps in the present CSC knowledge by comprehensively reviewing the CSC literature to date.
2) To design, fabricate and install a CSC system in Dublin.
   o To outline design and fabrication decisions and thereby provide a rationale for the specific CSC experimental system design.
   o To investigate suitable concrete mixtures for CSC applications, for optimum conductivity.
   o To investigate suitable colours and finishes for CSC applications, for optimum absorptivity.

3) To experimentally investigate the performance of a CSC system.
   o To monitor and analyse the thermal response of the CSC for all seasons of the year.
   o To calculate the hot water energy savings throughout the year.
   o To examine the influence of different operating conditions on the thermal and energetic response of the system.

4) To numerically model a CSC.
   o To develop a novel 3D model of a CSC system.
   o To validate this model with the experimental results.
   o To compare the performance of a CSC in different European climates.
   o To develop and validate a simplified model of a CSC for a parametric investigation that can be used to achieve results with significantly less computational effort.
   o To identify an optimum CSC through extensive parametric investigation.

5) To investigate the economic feasibility and applicability of CSCs.
   o To calculate the cost and hence feasibility, of different CSCs and CSC systems.
   o To calculate the payback period for the CSCs in different climates.
   o To conceptually investigate the range of potential applications of CSCs, and thereby outline future research.
1.3 Thesis outline

This thesis is structured into seven subsequent chapters (Chapter 2 to Chapter 8), each of which fulfils or partially fulfils one or two of the above objectives. The following is a summary of each of these subsequent chapters.

Chapter 2: Literature Review

This chapter of the thesis contains a comprehensive literature review, focusing on façade integrated solar thermal technologies (Section 2.2) and concrete solar collectors (Section 2.3). It highlights gaps in the current façade integration and CSC knowledge, forming the motivation for the remainder of this thesis. This chapter is focused on those aims outlined in Objective 1.

Chapter 3: Materials and Methods

This chapter is divided into three core sections. Section 3.1 describes the CSC experimental system design, fabrication and installation. It also outlines the measurement sensors and calibration techniques used. Section 3.2 explains the material characterisation of the concrete absorber, specifically the surface absorptance and the thermal conductivity. Section 3.3 presents an overview of the modelling software used to simulate CSCs. This chapter covers Objective 2 and forms the foundations for achievement of Objectives 3 and 4.

Chapter 4: Performance Evaluation of a Concrete Solar Collector

This section experimentally analyses the performance of the installed CSC system. The performance indicators are first defined in Section 4.1. The seasonal performance of the system is assessed in Section 4.2 by presenting the energy output for winter, spring, summer and autumn and comparing (i) a clear day, (ii) an average day and (iii) a cloudy day for each of these seasons. In Section 4.3 the operating temperatures of the experimental system is then assessed over a six-day reference period in March, which includes both clear and cloudy days. Section 4.4 addresses the performance implications of any changes made to the system. This chapter addresses Objective 3.

Chapter 5: Simulating the Performance of a Concrete Solar Collector

Chapter 5 presents a novel 3D model of a CSC and a model of the CSC as part of a hot water preheating system. The CSC model and system model are validated with the experimentally obtained results. Thermal graphics of the numeric CSC model are presented for various stages in the day. The system is compared with other possible CSC system configurations. The potential energy savings for two other European climates are also examined. Objective 4 is partly fulfilled in this chapter.
Chapter 6: Concrete Solar Collector Optimization

In Chapter 6 a simplified 2D model of a CSC is described, which is developed to conduct an in-depth parametric investigation of CSCs with reduced computational requirement. The parametric investigation identifies the optimum CSC configuration. Practical and aesthetic constraints are also outlined resulting in an optimum CSC configuration with reference to these practicalities. The optimum CSC is compared with the experimentally tested CSC. This chapter completes Objective 4.

Chapter 7: Applications and Economics

Chapter 7 identifies the heating systems, façade types and building typologies most suited for these CSCs. Chapter 7 also investigates the cost of the materials used to construct a CSC and uses these costs and the energy savings estimations to calculate the payback period of a CSC. Objective 5 is answered in this penultimate chapter.

Chapter 8: Conclusions and Recommendations

The key conclusions deriving from the research study are presented in Chapter 8. These include conclusions related to collector performance, optimum design and cost feasibility. The conclusions refer to the objectives outlined here. Future research recommendations are also outlined in Chapter 8.
Chapter 2

Literature Review
2 Literature Review

This chapter is divided into three primary sections. Standard solar thermal technologies, most common to rooftop applications, are first introduced in Section 2.1. Following this, a comprehensive literature review of fluid based Solar Thermal Facades (STFs) is presented in Section 2.2. This review section highlights a paucity of research on concrete solar technologies or collectors that can be integrated with concrete cladding systems. This lack of concrete products and knowledge of their operation is a key motivation for this research. Therefore, an in-depth review of the current state-of-the-art of all concrete solar collectors is presented (Section 2.3).

2.1 Solar thermal technologies

Solar thermal technologies, or Solar Thermal Collectors (STCs), convert energy from the sun into useful heat. Those collectors suitable for building integration can be separated into five core technology types.

A) Unglazed Collectors (UC),

B) Glazed Flat Plate Collectors (FPC),

C) Massive Solar Thermal Collectors (MSTC),

D) Evacuated Tube Collectors (ETC) and

E) Concentrated Solar Collectors.

Simplified section and plan drawings of each collector (A-E) are shown in Figure 2.1. To provide a strong foundation for this literature review, the collectors are first reviewed with reference to five core components: (1) cover, (2) absorber, (3) heat transfer fluid network, (4) insulation, and (5) fixings and framing systems. Components (1-4) are indicated in Figure 2.1.

The standard roof-attached technologies differ in performance and appearance, but each follows a similar heat transfer process. Solar radiation incident on the collector is captured by its absorber (2), this heat is then transferred to the piping network (3) via conduction through the absorber and finally to the working fluid by a combination of conduction and convection. As the collector temperature exceeds the ambient temperature, heat is lost by conduction, convection and radiation, and can be reduced by the inclusion of insulation (4) at the back as well as a vacuum or air space between a cover (1) and absorber (2).
2.1.1 Unglazed collectors

Unglazed Collectors (UC) (Figure 2.1 (A)) consist of a hydraulic piping system connected to, or forming an integral part of, an absorber layer that captures the solar radiation and transfers the heat to the circulating fluid. The UC may also include insulation at the back. High convective heat losses are characteristic of the UC due to the absence of a covering (Bonhôte et al., 2009; Tripanagnostopoulos et al., 2000), which reduces the collector’s efficiency. Convective heat losses become proportionally significant when large temperature differences occur between the ambient air and the absorber. For this reason they are commonly used in lower temperature applications, such as swimming pool heating (Energie Solarie SA, 2015; IEA, 2012) and water preheating for Domestic Hot Water (DHW) or space heating (Bonhôte et al., 2009). An advantage of UCs is their lower cost relative to other collectors. UCs account for 8.4% of the global installed solar thermal capacity and 4.5% of the European installed capacity (Weiss & Mauthner, 2014).

2.1.2 Flat plate collectors

The Flat Plate Collector (FPC) (Figure 2.1 (B)) is an advancement of the UC design and includes glazing on the front of the panel, offset by an air gap from the absorber, which reduces convective heat losses to the exterior. The piping system is bonded to the front or back of the absorber plate, or forms an integral part of the plate (Duffie & Beckman, 2013). Insulation is located behind the piping system to reduce conductive heat losses through the back and edges. Water temperatures of up to 80°C can be achieved with standard FPCs (Wang et al., 2015).

FPC technology has seen significant research focus and advancement in recent years (Sadashivkumar and Balusamy, 2014; Shukla et al., 2013). One innovation has seen the addition of selective coatings that has decreased absorber emittance, enhancing performance (Wijewardane & Goswami, 2012). Other innovations include increasing the cover efficiency via selective coatings for glazing (Ehrmann &
Reineke-Koch, 2012), reducing heat loss through improved insulation and evacuated systems (Beikircher et al., 2014) and improving the heat transfer, via geometrical optimization of the piping network (Jaisankar et al., 2009; Kumar & Prasad, 2000). These progressions have resulted in improved efficiency and increased product choice. FPCs account for 26.4% of the global installed solar thermal capacity and 84.9% of the European installed capacity (Weiss & Mauthner, 2014).

2.1.3 Massive solar thermal collectors

Massive solar thermal collectors (MSTC) (Figure 2.1 (C)) are opaque solar collectors that use high capacitance materials in place of highly conductive metals (D’Antoni & Saro, 2012). They have a similar configuration to under-floor heating or thermally active building systems (TABS) but rather than transferring heat from a heated fluid to a massive material, such as concrete, they instead aim to extract heat from the sunlight exposed material and transfer it to a circulating fluid (Lehmann et al., 2007; D’Antoni & Saro, 2012).

Asphalt and sand have been used in large scale MSTCs. Asphalt solar collectors have been reviewed in detail by Bobes-Jesus et al. (2013) and have been shown to both reduce the heat island effect as well as providing a source of thermal energy (Nasir et al., 2017; Nasir et al., 2015; Chiarelli et al., 2017). The thermal conductivity, pipe embedment depth and the surface absorptance are highlighted as key asphalt collector performance parameters (Guldentops et al., 2016). For building applications concrete provides a more suitable massive material and these collectors are referred to in this thesis as Concrete Solar Collectors (CSCs). They have a lower thermal output than the standard FPC, however, they are simpler to develop and have a lower cost (D’Antoni & Saro, 2012). Additionally, their inherent durability, structural strength and resistance to outdoor conditions means building integration can be achieved with fewer maintenance issues (D’Antoni & Saro, 2013; Kuhn, 2012; Sarachitti et al., 2011). A practical advantage of both concrete and asphalt collectors is that they use cheap abundant materials as the absorber.

More recent research has focused on the material and geometric optimization of CSCs. Increasing the conductivity of the concrete by incorporating metallic material into the concrete matrix improves the thermal performance (Keste & Patil, 2012; Krishnavel et al., 2014). Glazing and insulation can also be integrated in a multi-component panel design to reduce heat loss, however these inclusions come with a greater cost (Hazami et al., 2005; Hazami et al., 2010).

2.1.4 Evacuated tube collectors

Evacuated Tube Collectors (ETC) (Figure 2.1 (D)) are composed of an array of evacuated glass tubes. The heat transfer network of pipes or channels is connected to an absorber contained within the
evacuated tubes. ETCs can achieve higher temperatures than the FPC. In the tubes of ETCs temperatures can reach over 95°C (Wang et al., 2015) due to the vacuum-sealed absorber configuration. Advancements in ETC technology include geometrical enhancements of the absorber (Kim & Seo, 2007; Perez et al., 1995) and the addition of coatings on the tubular surfaces (Joly et al., 2013).

ETCs account for 64.6% of the global installed solar thermal capacity and 9% of the European installed capacity (Weiss & Mauthner, 2014). UCs and FPCs are most suitable for systemised façade integration because of their inherently flat geometry (Yang & Yu, 2011). But ETCs have been integrated in bespoke designs such as on balcony guardrails (Behling, 2015; Schweizer Energie, 2015).

2.1.5 Concentrating collectors

Concentrating solar thermal collectors are used to generate hot water or steam, generally in large industrial installations. These are commonly realised as line-focus collectors or point-focused collectors (Wang et al., 2015). The sunlight is concentrated, using mirrors or lenses, to heat fluid to high temperatures.

Concentration techniques, as referred to in this study, are also used for smaller scale applications (Figure 2.1 (E)) to boost the collector’s efficiency. Compound Parabolic Collectors (CPC) are stationary concentrating systems which have an optimised double parabolic trough geometry (Norton et al., 1994). They are typically applied in conjunction with ETCs to provide for DHW or space heating applications (Kalogirou, 2004). Concentrating solar thermal collectors are not commonly integrated into buildings, however, the geometry and concentration technology have inspired some novel research (Behling, 2015; CASE, 2015; Tanaka, 2011).

2.2 Solar thermal facades

Different issues arise when integrating the discussed STCs into the façade of a building. If STCs are to be considered for integration into the façade they need to be considered early in the design process and in relation to other façade components to ensure a seamless architectural design. STCs are often criticised for their appendage to roof and envelope and disunity with the building architecture. Integration with the building façade provides the potential for the renewable technology to become a more essential element of the building architecture. However, the wide-range of contemporary architectural facades necessitates a greater diversity of STF products, particularly if the integration of solar thermal technologies in the façade is going to become more commonplace. Providing options, in terms of colour, texture and dimension is key to the success of STFs as architectural components (Munari Probst & Roecker, 2007; Probst & Roecker, 2012). Current research on STFs focuses primarily on expanding the range of colours applicable to the cover or absorber. Other components of STFs, including the framing and fixing to the façade, have received less academic research focus.
Interest in, and hence publication of, STF research technologies and applications has seen a considerable increase in the last five years. The number of publications specifically related to liquid based solar thermal façade integrated collectors is categorised by publication date in Figure 2.2.

![Figure 2.2. Liquid based solar thermal façade integration studies by number and date, from 1998 to July 2017.](image)

A clear increase in research focus on the building integration of solar thermal collectors is observed in Figure 2.2 from 2012. It is unlikely to be a coincidence that this notable increase in research coincides with the IEA Task 41 for ‘Solar Energy and Architecture’ (IEA SHC, 2008) and the COST action TU1205 for ‘Building Integration of Solar Thermal Systems’ (COST, 2012). The number of publications for 2017 is expected to increase by the end of the year, continuing this trend.

### 2.2.1 Rationale for façade integration

The reasons for the facade integration of STCs, as well as the benefits of doing so, are expanded on below:

1. **Increased surface area.** The renewable thermal energy provision of a building can be increased by exploiting the façade surface. STFs are particularly appropriate for buildings with a high Hot Water Consumption (HWC), but limited roof space, including for example: apartments, hotels and hospitals (O’Hegarty et al., 2015). Specifically these technologies are pertinent to buildings with low roof to envelope ratios common to medium to high-rise buildings in urban environments. (Chow et al., 2005; Chow et al., 2006; Shi et al., 2013)
2. **Competition for roof space.** Ventilation boxes and other HVAC (Heating Ventilation and Air Conditioning) components are often located on the roofs of buildings, creating a competition with STCs for roof space. Furthermore, in warmer climates, building designers see the roof area as a valuable area for swimming pools and restaurants. This also creates competition for the space, highlighting the facade as an alternative location for renewable technologies in these locations.

3. **Multi-functional façade elements.** STFs can fulfil a range of functions in addition to hot water production, including insulation, screening and sun shading. Innovative designs have integrated solar thermal systems into balconies and shading devices (Abu-Zour et al., 2006; Li et al., 2015).

4. **Offsetting of materials.** When an STC is integrated into the façade, the total embodied energy associated with the building can be reduced since the embodied energy of the facade element plus an attached STC would be greater than a hybrid of the two (Greening & Azapagic, 2014).

5. **Piping heat loss reduction.** Transporting the solar heated fluid from roof mounted panels to ground floor storage tanks, and subsequently to taps can result in heat loss. Positioning STCs on the building facade has been proposed to reduce this long transmission distance, particularly in medium to high-rise buildings (Cuadros et al., 2007; He et al., 2014). This is also one reason why the building integration of solar thermal collectors is more valuable than that of building integrated photovoltaic (BIPV) technology. PV panels can be installed in remote areas and connected to the electrical grid. Energy losses from solar thermal systems are far more significant, thus, locating the supply as close as possible to the demand is paramount for an efficiently operating STS.

6. **Increased product choice.** The facade integration of STCs opens a new market. This increases the number of products available to specifiers of solar thermal technologies, thereby, increasing the potential for adoption and use of solar thermal technologies (REN21, 2014; Cappel et al., 2014).

2.2.2 Review of components

The individual components of an STC (presented for each STC type Figure 2.1) are discussed here in relation to STFs, beginning with the transparent cover (2.2.2.1) at the front and finishing with the fixing system at the back (2.2.2.5).

2.2.2.1 Cover

The transparent cover (component 1 in Figure 2.1), typically made from glass, is an essential part of FPC and ETC technologies and may also be used with MSTCs and concentrating technologies. The cover reduces thermal losses through the front but also reduces the amount of sunlight reaching the absorber (i.e. the optical efficiency), to an extent dependent on the transmittance value of the glass.
Research related to the cover of STFs focuses predominately on providing a range of different colours, and achieving this through the use of thin film technology. The aim of these thin film technologies is to produce a colour by achieving a high transmittance over the whole of the solar spectrum but a narrow peak reflectance in the specific visible range of the desired colour. Thin films with these characteristics were initially proposed by Schüler et al. (2004) for building integrated solar thermal applications, then succeeded by simulation and experimental studies using different film deposition methods including reactive magnetron sputtering (Boudaden et al., 2004; Boudaden et al., 2005; Mertin et al., 2013), sol-gel dip coating (Schüler et al., 2006) and spray pyrolysis deposition (Dudita et al., 2014). The sol-gel dip coating technique is most suited to large scale applications, such as solar collector glazing (Schüler et al., 2006). In general, the results showed that lighter colours (e.g. yellow) achieved a greater performance than darker colours (e.g. blue) when applied to the cover of solar thermal collectors (Schüler, Boudaden, et al., 2005; Schüler, Roecker, et al., 2005; Schüler et al., 2006).

2.2.2.2 Absorber

The absorber (Component 2 in Figure 2.1) is a critical component of all STCs. To maximise solar energy capture, the collector’s absorber is typically given a dark coating with an associated high absorptance value. Applying colour to the absorber of an STF, reduces the absorptance and subsequently reduces the efficiency (Kalogirou et al., 2005). A reduction in the emittance is also associated with colour inclusion. A reduction in the emittance results in reduced radiant heat loss through the front of the collector increasing the collector’s efficiency at greater temperature differences. For optimum performance, the absorber would have high conductivity, a high absorptance and a low thermal emittance.

For a higher optical efficiency, spectrally selective coatings have been applied (Orel & Gunde, 2001). These coatings have a high absorptance (between 0.3 and 2.5 µm) and a low thermal emittance (above 2.5 µm). While research has been conducted on spectrally selective coatings since the 1970s (Hutchins, 1979), coloured spectrally selective coatings are a topic of more recent research (Orel et al., 2005; Orel, Spreizer, Slemenik Perše, et al., 2007; Orel, Spreizer, Šurca Vuk, et al., 2007; Wu et al., 2013; Zhu et al., 2012; Zhu & Zhao, 2010).

The absorber is generally manufactured from highly conductive metals including copper (thermal conductivity \(k \approx 380 \text{ W/mK}\)), aluminium (\(k \approx 160 \text{ W/mK}\)) and steel (\(k \approx 50 \text{ W/mK}\)) (BS ISO 10456, 2009). Ceramics have also been investigated as a cheaper absorber material, suitable for facade integration (Yang, Wang, et al., 2013; Yang, Cao, et al., 2013; Sun et al., 2014; Xu et al., 2014). They have a lower thermal conductance (\(k \approx 2.3 \text{ W/mK}\)) but also have a lower cost (Sun et al., 2014). Polymers have also been considered as an absorber material because of their lighter weight and lower cost (Tsilingiris, 1999) and have led to the development of polymer absorbers for facade integration.
(Aventa Solar, 2015). However, they have a particularly low conductivity \( (k \approx 0.2\text{W/mK}) \). Concrete is typically the absorber material for MSTCs. As with ceramics and polymers, the thermal conductivity \( (k \approx 1 - 2\text{W/mK}) \) and price are lower. However, an advantage of concrete is that it is already used as a precast cladding component for facades.

It has been highlighted by Aventa Solar (2015) that many exterior and insulation finishing systems which are installed cause overheating as a result of the high temperatures of the absorber (when used for higher temperature applications), making a case for cheaper, less conductive materials.

2.2.2.3 Heat transfer network

The heat transfer network can refer to both the pipes within the solar thermal collectors, and those running from the collector to the tank and subsequently to the user. The heat transfer network within the collectors refers to the pipes, tubes or channels that transfer the fluid (Figure 2.1 (3)).

The hydraulic resistance of solar thermal collectors is reduced by using heat pipes, which use a combination of phase transition and conductivity to transfer the heat from the heat pipes to the exterior network while avoiding fluid mixing. Rassamakin et al. (2013) developed a novel STF where the heat pipe forms an integral part of a flat absorber. The versatility, scalability and adaptability of the system make it ideal for facade integration.

2.2.2.4 Insulation

Thermal insulation (Figure 2.1 (4)) can be included in FPCs, UCs and MSTCs to reduce the heat loss from the back and edges of the collector. Back insulation thickness of a standard STC commonly ranges from 0.04 - 0.075 m (Peuser et al., 2010), offering U-values of between 0.75 W/m²K and 0.42 W/m²K for an insulation conductivity of 0.03 W/mK. In many countries, a thicker insulation layer is required for STFs to ensure the envelope abides by building regulation specified U-values. An insulation thickness of between 100 and 140 mm, depending on insulation conductivity, is required to achieve a wall U-value of 0.21 W/m²K in Ireland (TGD Part L, 2011).

On the other hand, considering the high temperature reached by the absorber plate, heat radiating to the interior space of the building can promote overheating if not appropriately insulated (Ji et al., 2011; Matuska & Sourek, 2006; Salem & Pierre, 2007). This is particularly pertinent in the context of climate change where building overheating is widely expected (Kinnane et al., 2015). Heat transfer from the collector to the building interior is dependent on the variable exterior and interior conditions, as captured in simplified models by Maurer et al. (2015a).
When integrated directly into the building façade, the insulation contained in the STF can offset insulation that would otherwise be added to the façade. The embodied energy of insulation is high (Hammond & Jones, 2008) and offsetting this can facilitate the energy payback of the solar collectors.

2.2.2.5 Fixing and framing

The range of fixing and framing systems for STFs is wide and varied, and dependent on the collector and façade typology, as well as the building construction and structural system. Some novel STF products, particularly those meant for domestic use, continue to be attached proud of the façade, incorporating discrete fixing systems relative to many standard roof fixing systems (SolaCatcher, 2015). The aim for STFs is often for discrete integration in line with the building façade (Winkler Solar, 2015). Fixing solutions of commercial STF products are often proprietary and not commonly disclosed.

FPCs are typically encased in metal, commonly aluminium housing. In the context of curtain wall systems aluminium mullions and transoms are common, allowing for good matching of the collector frame with the façade framing system. A product range with varied material and geometrical casings allows for greatest adaptation to a wider range of framing systems. Nasov et al. (2014) developed an STF which can be installed in the existing frames of building windows.

With regard to façade systems STFs may be installed as curtain wall or rainscreen skins wrapping the building structure. A curtain wall detailing requires gaskets and/or face sealing between panels. Alternatively, the STF may be installed as a rainscreen offset and ventilated in which case moisture ingress through the skin can be evacuated via the cavity. Although the rainscreen system reduces the pressure on the outer face to deal with weather conditions, the performance of the STF is reduced due to the reduction in insulation. In both cases the STFs are installed on a secondary structure attached to the mullions and transoms or rails. For seamless aesthetic integration, façade elements that are non-active should match with or complement STF elements, as outlined by Munari Probst & Roecker (2007) following extensive surveying of architects. In the design of a full façade system these authors developed both STF and “dummy” elements that allow for the practical understanding of STF implementation in a well-considered overall façade design.

2.2.3 Solar thermal façade typologies

STFs also include novel solar thermal collectors that are integrated into areas of the façade other than the wall. Eight STF types are displayed and summarised in Table 2.1, providing examples for the commercially available STFs (i-iv) (Figure 2.1), along with presenting the advantages and disadvantages of each. Commercial examples include System (i) Winkler Solar’s VarioSol E, System (ii) Schweizer Energie’s Swisspipe Balkone, System (iii) Robin Sun solar thermal glass and System (iv) Energie Solaire’s AS Collector.
Table 2.1. Solar thermal facade types and their associated location, advantages and dis-advantages.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Location</th>
<th>Advantages</th>
<th>Dis-advantages</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>ii) ETC</td>
<td>Balcony</td>
<td>Adjustable absorber inclination, Material offsetting, Multi-functional</td>
<td>Connection difficulties</td>
<td>(Schweizer Energie, 2015)</td>
</tr>
<tr>
<td>iii) FPC/ETC</td>
<td>Transparent Facade Area</td>
<td>Disguised in facade, Multi-functional</td>
<td>Access difficulties, Connection difficulties, Performance reduction</td>
<td>(Robin Sun, 2015)</td>
</tr>
<tr>
<td>iv) UC</td>
<td>Opaque Facade Area</td>
<td>Range of colours, Cost, Ease of fabrication, Inherent flat surfaces</td>
<td>Performance reduction</td>
<td>(Energie Solarie SA, 2015)</td>
</tr>
</tbody>
</table>

System (i) Winkler VarioSol E has flexibility in terms of module sizes.

System (ii) Schweizer Energie’s, Swisspipe Balkone are installed onto balcony railing veneers of buildings.

System (iii) The Robin Sun solar thermal glass provides insulation, shading and hot water.

System (iv) Energie Solaire’s AS collector can be fitted to the facade as well as roofs.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Location</th>
<th>Advantages</th>
<th>Dis-advantages</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>v) ETC/FPC</td>
<td>Louvre</td>
<td>Adjustable absorber inclination, Multi-functional</td>
<td>Access difficulties, Connection difficulties</td>
<td></td>
</tr>
<tr>
<td>vi) FPC</td>
<td>Gutter</td>
<td>Disguised, Multi-functional</td>
<td>Access difficulties, Connection difficulties, Performance reduction</td>
<td></td>
</tr>
<tr>
<td>vii) MSTC</td>
<td>Opaque Facade Area</td>
<td>Cost, Disguised, Inherent flat surface, Material offsetting, Storage benefits</td>
<td>Access difficulties, Connection, Performance reduction</td>
<td></td>
</tr>
<tr>
<td>viii) FPC</td>
<td>Balcony</td>
<td>Inherent flat surface, Material offsetting, Multi-functional</td>
<td>Connection difficulties, Performance reduction</td>
<td></td>
</tr>
</tbody>
</table>

2.2.3.1 Unglazed collectors

STFs that enable varied form (shape, size and jointing of the individual modules) and material (surface texture, finish and colour) are adaptable with a multitude of façade designs. The SOLABS unglazed STF, which is inspired by existing façade metal claddings, is one such UC based STF that offers a range of options in terms of form and material (Munari Probst & Roecker, 2007). Another conceptual STF, based on the UC, uses aluminium profiled heat pipes to form a layer of the facade (Rassamakin et al., 2013). The benefit of this system is that a series of heat pipes can be joined with the piping within the building without the need to fabricate an entire collector. Rodríguez-Sánchez et al. (2014) developed a novel UC based STF with curved geometry. This enabled their integration on facades with curvaceous profiles, which are becoming increasingly common in contemporary architecture.

2.2.3.2 Flat plate collectors

A number of novel FPC based STFs have been designed. Nasov et al. (2014) have developed an STF, based on the FPC, which can be installed in existing window frames. A gutter-integrated solar thermal collector (Table 2.1. (vi)) is another example of where STFs have been developed based on the FPC technology. The product has been designed, experimentally tested and modelled (Motte et al., 2013a; Motte et al., 2013b; Notton et al., 2013). FPC based STFs have also been considered as replacements for balcony railings (Table 2.1. (viii)) (Ji et al., 2015; Yang, Wang, et al., 2013).

Triangular modules are the basis of many faceted façade types, enabling undulating and curved façade geometries. Visa et al. (2014) presented a new concept of FPC arrays based on triangular shaped modules to produce more options for implementation on a variety of building types. An optimised module of this kind reached an efficiency of 62% under indoor testing (Visa et al., 2015).

2.2.3.3 Massive solar thermal collectors

MSTCs are of many types and are varied in their application. MSTCs include absorbers built from asphalt, sand and concrete. With regard to the building façade, concrete solar collectors (CSC) are the most applicable. CSCs, in the form of precast concrete façade panels, may be configured as single skin panels anchored to the building structure, or incorporated in a sandwich panel configuration where the inner leaf of the concrete panel is load bearing. CSCs offer a cheaper alternative to other expensive STFs primarily because of their bulk mono-material makeup. Complex framing is not necessary and off-the-shelf precast fixing systems may be used.

A paucity of research and commercially available products exists for this type of STF. But, they provide a unique solution for the integration of solar thermal technology into precast concrete facades, where pipes are disguised in the concrete matrix.
2.2.3.4 Evacuated tube collectors

The tubular nature of the ETC restricts the potential integration of this technology into flat building facades. A number of alternative locations for this collector type are feasible, as presented in Table 2.1. One location for the building integration of ETCs is the balcony (Table 2.1 (ii)) (Ji et al., 2015; Li et al., 2015; Shi et al., 2013; Zhai et al., 2008; Zhai & Wang, 2008). ETC collectors include both direct and indirect (via heat pipes) heat transfer fluid networks and the geometric arrangement can change from one manufacturer to the other. It is the curved nature of the collector which is the primary area of concern with regard to façade integration.

Another location investigated for STFs, based on the ETC geometry, is the louvre or awning above windows (Table 2.1 (v)) (Palmero-Marrero & Oliveira, 2006; Abu-Zour et al., 2006) where a payback period of approximately 6 years was observed in Iberia (Palmero-Marrero & Oliveira, 2006). Indoor experimental results, on another louvre replacing collector with embedded heat pipes, showed that increasing the number of heat pipes within the louvre increased the efficiency without significantly affecting the cost (Abu-Zour et al., 2006).

2.2.3.5 Concentrating collectors

Concentrating solar thermal collectors are not commonly integrated into buildings, however, the geometry and concentration technology have inspired some novel research. A novel concentrating solar thermal collector, which uses partially perforated compound parabolic reflecting mirrors, has been developed for transparent facade integration (Behling, 2015). The perforation allows light into the building while only reducing the solar gain of the collector by 10%.

At a larger scale, facade integration of a vertical heliostat field on the south facing facade has been considered, and is at a conceptual stage (González-Pardo et al., 2014; González-Pardo et al., 2013). The array of mirrors located on the facade reflects solar energy onto a receiver tower, the dimensions of which depends on the final energy application.

2.2.3.6 Partially transparent solar thermal facades

Rather than developing an STF from the standard solar thermal technologies, the opposite design process may be adopted, whereby, an element of a facade is developed to harvest solar energy. These STFs are typical for the transparent section of a building’s facade. These partially-transparent STFs can also provide shading and insulation (Table 2.1 (iii)). A novel transparent solar thermal collector has been installed on a pilot building in Ljubljana, Slovenia (Hermann et al., 2008; Maurer et al., 2012). Initial results from this field study showed that solar gain did not vary significantly over the year. A model for transparent solar thermal facades has also been developed by Maurer & Kuhn (2012) which can predict their performance and can also be integrated with whole building system simulation.
2.3 Concrete solar collectors

The rational for façade integration of solar thermal collectors has been outlined. An extensive literature review has also been conducted to highlight the current available STF technologies and identify the areas for potential future research. A lack of research on concrete solar collectors as a façade integration solution exists and hence is the focus of this research. This section investigates the state-of-the-art of CSCs.

2.3.1 Background

Concrete solar collectors are a subcategory of the Massive Solar Thermal Collectors (MSTCs), as defined by D’Antoni & Saro (2012), which are opaque solar collectors that use high capacitance materials in place of highly conductive metals. CSCs are a type of MSTC that can be used for façade integration. High-capacitance materials have been considered as a cheap alternative to typical absorber materials (steel, aluminium, copper etc.) since the 1970s and 80s (Olive, 1977; Kumar et al., 1981; Sedgwick & Patrick, 1981; Srivastava et al., 1982; C. Kutscher, 1984; Turner, 1986; Turner, 1987). Asphalt and sand are materials that have been used in MSTCs but concrete (which is applicable to buildings) is the focus of this thesis. CSCs have a lower thermal output, when compared to the standard STCs, but their suitability for building integration is advantageous since precast concrete panels already have a place in the current cladding market.

These collectors might be best understood as the reverse of underfloor heating (Lehmann et al., 2007; D’Antoni & Saro, 2012). The surface is exposed to solar radiation and the heat is conducted from the concrete to the circulating fluid. Furthermore, storage effects are induced because of the high-capacitance nature of the absorber. This means heat can be obtained from the solar collector at periods when no solar radiation is available (D’Antoni & Saro, 2012). A passive concrete collector was set up by Bilgen & Richard (2002) to examine the transient effects of temperature within the concrete. They found that the storage capacity and thermal performance increased positively with the thickness of the slab.

More recent research has focused on the material and geometric optimization of CSCs. Increasing the conductivity of the concrete by incorporating metallic steel fibres and iron scrap metal into the concrete matrix has been shown to improve the thermal performance (Keste & Patil, 2012; Krishnavel et al., 2014). However, detail on the mixture designs and associated conductivity of these concrete mixtures were not presented in the work. Furthermore, glazing and insulation can be included to reduce unwanted heat loss, but these inclusions may also require a framing system, which would reduce the CSC’s potential applicability for facade integration (Hazami et al., 2005; Hazami et al., 2010).
2.3.2 Façade integration

In addition to a reduction in cost of the collector, the distinguishing structural nature of CSCs means a framing system is not necessary, creating a significant advantage for façade integration. The majority of CSCs have been conceived for separate roof attached installations (Nayak et al., 1989; Bopshetty et al., 1992; Al-Saad et al., 1994; Jubran et al., 1994; Hazami et al., 2005; Hazami et al., 2010; Keste & Patil, 2012; Krishnavel et al., 2014), as well as horizontal roof integrated installations (Kumar et al., 1981; Sarachitti et al., 2011). Vertically inclined CSCs have also been considered theoretically (D’Antoni & Saro, 2013) and experimentally (Chaurasia, 2000). Chaurasia (2000) studied the influence of different inclination angles, at noon on a typical day in November (in India), outlet hot water at a temperature of 42°C was reached (for an inlet temperature of 20°C) for a vertically installed collector; approximately 7°C higher than an identical horizontally installed collector at the same time and location. These results show promise for an optimal performing façade integrated concrete solar collector, but the results were not further expanded on.

2.3.3 Concrete solar collector parameters

A range of geometric and material parameter values are found in the literature, often with little explanation given to the rationale for selecting individual parameter values. Framing means a cover (typically glass) and insulation can be easily included, which improves the thermal performance by reducing heat loss (Hazami et al., 2005; Hazami et al., 2010; Keste & Patil, 2012). However, this also significantly increases the cost of the collector and may compromise the collector’s aesthetic which is important for façade integration, as highlighted in the literature on façade integrated collectors. In an extreme temperature climate, Krishnavel et al. (2014) showed that a CSC with aluminium pipes had peak outlet water temperatures of 65°C and 62°C with and without a cover respectively, illustrating a small increase in the performance as a result of including a cover for their particular design.

Other performance enhancements can be achieved, without the need for a framing system, such as increasing the concrete’s absorptance and conductivity. Enhancing the surface’s optical properties can increase the amount of solar radiation captured by the CSC and reduce the amount of heat lost to the ambient. Unfinished concrete has a solar absorptance, $\alpha$, of approximately 0.65, which can be improved to 0.96 by painting the concrete’s surface black (Keste & Patil, 2012). The optical properties could be further enhanced by applying a spectrally selective coating to the concrete face (Hazami et al., 2005). Positive influences on the CSC’s efficiency have also been observed for a reduction in the pipe embedment depth (Kumar et al., 1981), a reduction in the pipe spacing (Nayak et al., 1989) an increase in the pipe’s external diameter (D’Antoni & Saro, 2013) and an increase in the conductivity of the pipes (Al-Saad et al., 1994) and concrete absorber (Krishnavel et al., 2014).
The majority of the experimental research on CSCs has been conducted in countries with warm climates, including India (Kumar et al., 1981; Nayak et al., 1989; Chaurasia, 2000; Keste & Patil, 2012; Krishnavel et al., 2014), Jordan (Al-Saad et al., 1994), Tunisia (Hazami et al., 2005; Hazami et al., 2010) and Thailand (Sarachitti et al., 2011). There is a paucity of experimental research on the performance of CSCs in cooler climates.

2.3.4 Performance

This section describes the CSCs that have been experimentally investigated. The prototypes, found in the literature, are summarised by their design and associated performance results. Drawings of the described designs, with dimensions (mm), are produced in Table 2.2. Additionally, the materials and additional elements used are described.

Unlike standard solar thermal technologies, which are defined by an instantaneous efficiency curve, a common performance indicator has not been established for CSCs. Typically, the efficiency of classical STCs is evaluated using instantaneous measurements. The non-negligible thermal mass of concrete solar collectors means that typical instantaneous Hottel-Whillier-Bliss (HWB) performance curves are not appropriate for CSC analysis. The useful energy output, $Q_u$, of an FPC (with negligible thermal mass) is defined as:

$$Q_u = Q_i - Q_l$$

where $Q_i$ is the total instantaneous energy gain and $Q_l$ is the instantaneous energy loss. Based on this energy balance, the Hottel-Whillier-Bliss relationship for the useful energy gain, $Q_u$, is defined by Eq. (2.2) (Duffie and Beckman, 2013).

$$Q_u = A_c F_R [G(\tau \alpha) - U_i (T_i - T_a)]$$

where $F_R$ is the heat removal factor; included to compensate for the assumption that the average collector temperature is represented by the fluid inlet temperature, $T_i$. $T_a$ is the ambient temperature. The transmittance-absorptance product, $(\tau \alpha)$, is based on the optical properties of the cover and absorber of the collector (Figure 2.1 (1) & (2)). The total thermal transmittance, $U_i$, is the sum of thermal transmittance through the front, back and edges of the collector. Because MSTCs exhibit non-negligible storage effects an additional storage term, $Q_s$, is added to Equation 2, to become Equation 3, and the HWB relationship is no longer valid. The positive/negative influence of the stored energy, $Q_s$, on the useful energy gain, $Q_u$, changes throughout the day depending on associated external conditions.
\[ Q_u = Q_f - Q_l \pm Q_s \quad \text{Eq. (2.3)} \]

The useful energy output, \( Q_u \), is not commonly used throughout the literature when referring to the performance of a CSC. Some studies refer to the maximum outlet fluid temperature with values varying between 33 °C and 65 °C (Chaurasia, 2000; Hazami et al., 2005; Keste & Patil, 2012; Krishnavel et al., 2014; Kumar et al., 1981). Other studies refer to the daily efficiency with values ranging from 28% to 40% (Al-Saad et al., 1994; Hazami et al., 2010; Kumar et al., 1981; Nayak et al., 1989). Very low payback periods of between 2 and 3 years are found throughout the literature. The performance indicators used in this work are described in Section 4.1.

2.3.5 Concrete conductivity

A literature review of CSCs highlighted the range in values obtained (or selected) as the thermal conductivity of the concrete mixture. Values ranged from 0.72 W/mK (Kumar et al., 1981) to 4 W/mK (Keste & Patil, 2012), with an average value of 1.27 W/mK. The highest thermal conductivity of 4 W/mK was obtained by incorporating “scrap metal” into the concrete mixture, however no detail is provided on how this value is measured or what the constituent proportions of the concrete mixture is.

Most studies within the literature, that are concerned with the thermal conductivity of concrete, focus on reducing the conductivity to reduce the thermal transmittance in walls. This can be achieved by replacing standard aggregates with, for example, lightweight aggregates (Liu et al., 2014; Yun et al., 2013), recycled aggregates (Zhu et al., 2012) and even hemp (Collet & Pretot, 2014; Walker & Pavía, 2014).

For CSCs it is desirable to increase the conductivity. Other rationale for increasing concrete conductivity includes bridge deck de-icing (Tuan, 2004), reducing temperature gradients in large concrete pours (Howlader et al., 2012; Sedaghat et al., 2014; Xu & Chung, 2000), electrical grounding construction (Tian et al., 2012) or adjusting thermal mass (Wadsö et al., 2012). While a thermally conductive concrete is desirable, it should not come at such a cost that would omit one of the primary advantages of CSCs i.e. their cost effectiveness. Furthermore, a workable concrete is desirable to achieve a good contact with the pipes embedded within the concrete matrix. These practical considerations are accounted for when selecting the concrete mixture in this study.
<table>
<thead>
<tr>
<th>Reference and Geometry</th>
<th>Location</th>
<th>Piping</th>
<th>Insulation</th>
<th>Glazing</th>
<th>Paint/coating</th>
<th>Additions</th>
<th>Performance criteria:</th>
<th>Result</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Maximum temperature rise:</td>
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<td></td>
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<td>Galvanised wire mesh</td>
<td><strong>Daily efficiency:</strong></td>
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<td>Glass reinforced concrete</td>
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<tr>
<td></td>
<td>India</td>
<td>USA</td>
<td>India</td>
<td>Israel</td>
<td></td>
<td></td>
<td>Daily efficiency:</td>
<td></td>
</tr>
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<td></td>
<td>Concrete passage ways (no piping)</td>
<td>PVC (polyvinyl chloride)</td>
<td>Conduit lattice</td>
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<tr>
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</tr>
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<td>Reference and Geometry</td>
<td>Location</td>
<td>Piping</td>
<td>Insulation</td>
<td>Glazing</td>
<td>Paint/coating</td>
<td>Additions</td>
<td>Performance criteria</td>
<td>Result</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------</td>
<td>--------</td>
<td>------------</td>
<td>---------</td>
<td>---------------</td>
<td>----------</td>
<td>---------------------</td>
<td>--------</td>
</tr>
<tr>
<td>A-Brodl et al. (1994)</td>
<td>Jordan</td>
<td>Galvanised steel, Propylene glycol and Polyvinyl chloride</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>Daily efficiency: 40% for galvanised steel pipes</td>
<td>Fluid temperature: Between 36°C and 58°C</td>
</tr>
<tr>
<td>Chaurasia (2000)</td>
<td>India</td>
<td>Aluminium</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>-</td>
<td>Maximum collector fluid temperature: 58°C</td>
<td>Payback period: 3 years</td>
</tr>
<tr>
<td>Hazami et al. (2005)</td>
<td>Tunisia</td>
<td>Capillary braid</td>
<td>Polyethylene</td>
<td>Yes</td>
<td>Black coating</td>
<td>Spectrally selective black coating</td>
<td>Daily efficiency: 32%</td>
<td>Maximum collector fluid temperature: 50°C</td>
</tr>
<tr>
<td>Hazami et al. (2010)</td>
<td>Tunisia</td>
<td>Copper</td>
<td>Polyethylene</td>
<td>Yes</td>
<td>Spectrally selective black coating</td>
<td>-</td>
<td>-</td>
<td>Payback period: 3 years</td>
</tr>
<tr>
<td>Location</td>
<td>Thailand</td>
<td>India</td>
<td>India</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Piping</td>
<td>Polyvinyl chloride</td>
<td>Copper</td>
<td>Aluminium, Polyvinyl chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>No</td>
<td>wood</td>
<td>No</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Glazing</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Paint/coating</td>
<td>No</td>
<td>Black coating</td>
<td>Black coating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additions</td>
<td>Laid upon a reinforced concrete slab</td>
<td>Steel fibres and mesh</td>
<td>Scrap metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Performance criteria: Result**

- Output fluid temperature: between 40°C and 50°C
- Maximum output fluid temperature: 54°C
- Payback period: 2.5 years
- Maximum output fluid temperature: 65°C and 62°C for aluminium pipes with and without glazing
While graphene is one such material that has been shown to have a positive influence on the conductivity (Sedaghat et al., 2014; Tian et al., 2012; Tuan, 2004) its current cost does not warrant its inclusion for CSC applications. Magnetite is another material which showed positive influences in thermal conductivity (Wadsö et al., 2012) however these aggregates are not available in Ireland, and would increase the cost of the concrete as a result of shipping. Replacing aggregates with those of higher conductivity, increasing cement content (hence reducing the air-voids) and including metallic materials such as steel and metal manufacturing bi-products provide a relatively cheap means of increasing conductivity. This research investigates the thermal performance of 5 such concrete mixtures using locally sourced materials.

2.3.6 Concrete solar collector models

Instantaneous efficiency-based models, such as the HWB model, neglect thermal mass meaning any heat stored in the concrete would be accounted for as a heat loss. While some of the heat stored in the concrete is eventually lost to the environment, some of the stored heat is extracted by the embedded pipes later in the day as useful heat. A transient analysis is therefore required to capture these thermal storage effects.

A number of 1D (D’Antoni & Saro, 2013; Sarachitti et al., 2011; Tanzer & Schweigler, 2016) and 2D (Abbott & Ellis, 2007; Bopshetty et al., 1992; Sokolov & Reshef, 1992) models have been developed, which do account for these storage effects, however, the geometry of the pipe parallel to the front absorbing surface are not captured in 1D and 2D models. CSCs have also been modelled successfully as part of novel solar thermal systems (Blecich & Orlić, 2012; D’Antoni & Saro, 2013; Tanzer & Schweigler, 2016). 3D models have been developed for asphalt solar collectors, another subcategory of massive solar thermal collectors, using Finite Element Analysis (FEA) software such as COMSOL Multiphysics (Basheer Sheeba & Krishnan Rohini, 2014; Guldentops et al., 2016) and ANSYS (Nasir et al., 2015). Models for pipes embedded in concrete have also been developed for concrete with embedded pipes for removing the heat of hydration in large concrete pours (Bofang, 2014; Ding & Chen, 2013; Liu et al., 2015; Yang et al., 2012; Zuo et al., 2015). The models however have significantly different applications and hence different boundary conditions, geometries and assumptions. To date, there is a paucity of detailed 3D models of CSCs, validated using real outdoor experimental conditions.

2.4 Gaps in knowledge

The literature review has identified gaps in the research which are the basis for this thesis. They are outlined below:

1. Concrete solar collectors for façade application.
4. Detailed, validated, 3D model of a CSC using dynamic boundary conditions.

The literature review is summarised in Figure 2.3.

Figure 2.3. Flow chart of Chapter 2. Literature Review.
Chapter 3

Materials and Methods
3 Materials and Methods

Descriptions of the materials and methods that define this research are presented in this chapter. First a summary of the proposed Concrete Solar Collector’s (CSC) experimental set-up is presented. This overview of the system is followed by an in-depth description of the design, fabrication and installation of the experimental set-up in Section 3.1. The data logging equipment and their associated uncertainties, which were used to quantify the performance of the system, are also described in Section 3.1. The performance properties of the concrete are investigated in Section 3.2. Finally, an overview of the software used in this work is outlined in Section 3.3.

3.1 Introduction to the experimental system

A schematic of the experimental system setup, with associated images, is displayed in Figure 3.2. The system consisted of three CSCs connected in series with an insulated hot water storage tank. The three CSCs were located on the roof of the Simon Perry Building in Trinity College Dublin. The full capacity of the storage tank was not used to accommodate the water draining back from the CSCs when the pump was switched off and to omit any spillages from pressure build up in the tank. A pressure release vent was also installed at the top of the tank to release air from pressure build up in the tank. Green dye was added to the fluid so that the fluid level can be checked easily. The storage tank was located on a bund to contain any spillages. The system was designed as a direct (or open loop) system, meaning that no heat exchangers are used and the water circulating through the collectors is the same water as that in the tank. The CSCs were installed at an elevation higher than the storage tank so that when the pump is switched off the water drains back inside the tank. This direct drain back system obviates the requirement of an antifreeze agent in the fluid.

Type K thermocouple sensors were installed at various locations in the system, as displayed in Figure 3.2. There are an additional three surface thermocouples (Ts4, Ts5 and Ts6) which are not displayed in the schematic as they are located on the backside of the collector (Ts5 is shown in the section cut B-B of Figure 3.2 to show exactly where they were located). A Kipp and Zonen CMP 11 pyranometer was used to measure the solar irradiance and a Young 05103 anemometer measured the average wind speed.

A DAB VA 55/130 pump was used to circulate the fluid and has three operating speeds. To enable additional flow rates through the collector a bypass was installed with a gate valve. The valve can be adjusted manually to change the flow through the collectors. The flow rate of the system was measured using an SM 8000 magnetic induced flow meter.
3.1.1 Concrete solar collector design

The design and construction of the concrete solar collectors used for experimental investigation is best described by following the path of Figure 3.1.

Figure 3.1. Concrete solar collector construction process.

i. A 1 m² area of concrete solar collector with a thickness of 0.08 m was first proposed. However, such a specimen would weigh just over 200 kg and require specialist equipment to transfer the concrete solar collector onto the roof. Instead three $0.6 \times 0.6$ m area collectors (each weighing 65 kg) were constructed and connected in series on the roof. The formwork for these three collectors was constructed out of plywood.

ii. Copper pipe is selected as the choice of heat exchanger for this experiment because closer spaced pipes are achievable when compared with Cross-linked polyethylene (PEX) piping. The copper pipe is cut into 0.6 m, 0.5 m and 0.05 m lengths. If larger surface areas are available PEX piping may be desirable given the greater resistance to corrosion and lower cost.

iii. The lengths were welded together into a serpentine geometry using copper elbows. Given the equipment available, welding was used instead of bending the pipe to maintain a reliable geometry. A serpentine geometry was used instead of the standard harp style heat exchanger to ensure uniform flow.
iv. The 15 mm diameter copper pipe heat exchanger was embedded at a depth of 20 mm beneath the concrete surface and raised above the base of the formwork by fixing the pipes to concrete spacers. A hole was made in the formwork for the inlet and outlet of the heat exchanger so they can be connected in series once lifted to the roof.

v. A concrete mixture was selected that had a relatively higher thermal conductivity than standard concrete mixtures while also being workable enough to guarantee good contact between the concrete and pipes with the addition of superplasticiser. This design process is discussed in greater detail in Section 3.2.1.

vi. The concrete for all three collectors was mixed in one batch and poured into the moulds in two layers. Each layer was vibrated on a vibration table for 15 seconds.

vii. The concrete solar collectors were cured for two weeks using wet hessian. Once cured sufficiently they were manually lifted onto the roof through a hatch door.

viii. The collectors were connected with plastic pipe and jubilee clips. The entire system was connected in series. The collectors were painted black to achieve the highest attainable solar absorptance.

ix. Once connected and painted the concrete solar collectors were tilted vertically and insulated at the back and edges (including the edges between the separate collectors to allow for the assumption of one long collector) to represent a south facing façade. They were connected to the guardrails at the parapets of the roof to prevent them falling during operation.

3.1.2 System design

The installed concrete solar collectors were connected to the storage tank (located inside) with plastic pipe. The plastic connection pipes were insulated and covered in reflective foil to reduce any heat gains or losses. Thermocouples were installed in their various locations following the schematic in Figure 3.2. The complete set-up on the roof top of the Simon Perry building is shown in Figure 3.3. The set-up of the tank connected to the collectors is depicted in Figure 3.4.

The location of the pyranometer and anemometer is also shown in Figure 3.3. The anemometer was located at 15 m east of the collectors, which is connected to a separate weather station. The pyranometer was orientated such that it is in line with the front face of the concrete solar collectors. A close-up of a surface thermocouple, the connection between each collector and the insulated connection pipes are also presented in Figure 3.3.
Figure 3.2: Schematic and associated photos of the experimental setup. Experimental design, fabrication and installation of a Concrete Solar Collector System.
Figure 3.3. Annotated picture of the concrete solar collector system (outdoors).

Figure 3.4 shows the part of the system that is located indoors and its associated components. A close-up of the data logger, calibration point, level, circulation pump, gate valve and pressure/flow meters are also presented.

It is an active system in that it uses a pump to circulate the fluid. The pump used has not been optimised for the system but is advantageous from an experimental point of view by offering three different flow rates. The pump uses electrical energy which is discussed and accounted for in Chapter 4.

Low flow rates (< 0.03 kg/s) are typical of serpentine pipe geometries (such as this collector) which have higher hydraulic resistance and subsequent higher pressure-losses (Dayan et al., n.d.). Other advantages of low flow rate systems are documented in the literature (Cristofari et al., 2003; Notton et al., 2014), such as improved thermal stratification. Thermal stratification is not capitalised on here because of the tank geometry and direct nature of the system inducing mixing in the tank. While this is a drawback in terms of performance, it allows for a simplification in modelling the tank, an advantage discussed in Chapter 5.
Figure 3.4. Annotated picture of the concrete solar collector system (indoors).

Because a hot water draw off has not been implemented in the system it is important that the tank is cooled down over night in order to obtain meaningful results over substantial periods of time. This is
achieved by continuously running the pump and the CSCs, which are cooled by the night sky, therefore cool down the fluid in the system.

3.1.3 Sensors and calibration

The equipment and calibration of individual sensors is presented here.

3.1.3.1 Data loggers

The data was obtained using a National Instruments data acquisition chassis (NI cDAQ 9174, 2017). A sixteen (NI 9213, 2017) and a four (NI 9211, 2017) channel analogue input module were used to obtain temperature and irradiance. They have a sensitivity of ± 80 mV. For logging the mass flow rate, a four channel analogue input module was used, which has a lower sensitivity of ± 10 V (NI 9201, 2017). The chassis and associated modules are displayed in Figure 3.5. The chassis is connected to a PC where a data acquisition program was developed in LABview. The program is described in Section 3.3.1.

![National instruments DAQ – 9174 Data logger chassis with installed 9211, 9213 and 9201 modules; before and after fully filling the sensor channels for the given application.](image)

3.1.3.2 Temperature sensors

Type K (Chromel / Alumel) sensors were used in this work because of their resistance to corrosion and strong linearity at temperatures between 0 and 100 °C. Figure 3.6 illustrates the different type K thermocouple wires, probes and connections used in this work.

![Type K thermocouples and type K connectors.](image)
The type K thermocouple cable (T_k) and thermocouple extension cable (T_kX) transfer a differential voltage to the data acquisition device which is converted to temperature. The robust T_kX wire was used to avoid damage for long distances, while the T_k wire or T_k probes provided the temperature reading. Depending on the measurement location, a different combination of the sensors and connection of Figure 3.6 were connected to the data acquisition device from Figure 3.5.

Errors for each temperature reading were a combination of the errors from the wires, connections and data logger. While type K sensors have a good linearity for the range of temperatures concerned within this experiment (linear relation between the output voltage and the temperature being measured), offset and slope errors remain. These errors are typically noted and the given sensor’s accuracy is simply presented, which can be > ± 1 °C in many cases. In this work correction factors were applied to account for the offset and slope errors reducing the uncertainty of each sensor to approximately ± 0.05 °C.

A two point calibration can be used where the sensor output is ‘reasonably linear’ over the measurement range, as is the case with type K thermocouples between 0 °C and 100 °C (Earl, 2016). A correction was applied at 0.01 °C (the triple point of water) and 100 °C (the boiling point of water). To ensure the thermocouples were at these known temperatures a calibration chamber was constructed where melting ice was placed in a beaker within a double insulation layered box (Figure 3.7). For the measurement of steam at 100 °C, the thermocouples were placed just over boiling water and the calibration was taken after approximately 5 minutes under this condition. All the thermocouples were assembled together with a reference pre-calibrated thermometer (error of ± 0.05 °C) for the calibration process.
When the reference thermometer was reading the same temperature (0 °C for melting ice and 100 °C for steam) for over a minute the calibration factor was committed in the LABview program. An additional third point was committed using the calibration chamber at ambient temperature (20 °C).

3.1.3.3 Flow rate measurement

The flow rate of the system was measured using an IFM SM 8000 magnetic induced flow meter. The flow meter comes with a real time display that displays flow rates with a digital output of one decimal place and serves as a useful tool for observing the approximate real time flow rate.

Figure 3.8. SM 8000 Magnetic induced flow meter.

Linear regression was used to obtain a calibration factor between the output voltage and the manually measured mass flow rates taken at the calibration point in the system (Figure 3.2). An $R^2$ value of 0.995 for flow rates between 0 and 0.06 kg/s was calculated, as displayed in Figure 3.9.

A linear relationship was taken from this and is expressed in Eq. (3.1).
Flow (kg/s) = (Voltage \times 0.178) – 0.033 

\text{Eq. (3.1)}

3.1.3.4 Wind speed measurement

A Young 05103 anemometer measured the average wind speed and was recorded on a separate data logger. A stand-alone Campbell scientific data logger, powered by a battery, was used and the anemometer had a manufacturer-specified accuracy of 0.3 m/s. The average wind speed was taken over a 10-minute period. So that the discrete measurements of the wind speed match all the other data recorded by the National Instruments data logger, a simple linear interpolation was used. Both logger and anemometer are displayed in Figure 3.10.

Figure 3.10. Young 05103 Anemometer and associated data logger.

3.1.3.5 Irradiance measurement

A Kipp and Zonen CMP 11 pyranometer (Figure 3.11) connected to the NI 9211 data logging module (Figure 3.5) was used to measure the solar irradiance. Errors of between ± 15.5 W/m² for 0 W/m² and ± 34.1 W/m² for 650 W/m² were calculated using the manufacturer’s specified values and following the Kipp and Zonen user manual (Kipp and Zonen, 2017; NI 9211, 2017). The calculated error accounts
for both inaccuracies with the data logger as well as the inaccuracies from the pyranometer. These include errors such as non-stability inaccuracies due to the age of the pyranometer.

3.2 Concrete characterisation

The novelty of the CSC, when compared with classical solar thermal collectors, is the concrete itself, which replaces the high conductive metal absorbers. It is therefore important to design a suitable concrete mixture. The concrete designs, the rationale for selecting the designs and the methods used to characterise them are described in this section. The results from the thermal conductivity testing and absorptance testing are also presented. For optimum performance, the concrete should have a high thermal conductivity relative to standard concrete so that it efficiently transfers the heat absorbed on the surface to the embedded pipes, it should also be workable so that good contact between the concrete and pipe is achieved. The density and structural strength of the concrete were also measured.

3.2.1 Concrete mixture designs

The mixture proportions of the five concrete mixtures are presented in Table 3.1. They are adapted from the mixture used by West et al. (2015) for concrete with a high dosage of steel fibres.
Table 3.1. Concrete mixture designs (proportions in kg/m³) and associated 50 × 50 mm section images.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Section cut</td>
<td><img src="image1" alt="Section cut" /></td>
<td><img src="image2" alt="Section cut" /></td>
<td><img src="image3" alt="Section cut" /></td>
<td><img src="image4" alt="Section cut" /></td>
<td><img src="image5" alt="Section cut" /></td>
</tr>
<tr>
<td>Cement</td>
<td>380</td>
<td>380</td>
<td>470</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>Water</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
</tr>
<tr>
<td>Sand</td>
<td>603</td>
<td>603</td>
<td>603</td>
<td>603</td>
<td>603</td>
</tr>
<tr>
<td>10 mm Limestone</td>
<td>1121</td>
<td>1121</td>
<td>1121</td>
<td>1121</td>
<td>1121</td>
</tr>
<tr>
<td>10 mm Quartzite</td>
<td></td>
<td>1121</td>
<td>1121</td>
<td>1121</td>
<td>1121</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td></td>
<td></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Superplasticizers</td>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

The five mixtures displayed in Table 3.1 address five potential areas for increased conductivity. The rationale for each is outlined below:

1. **Mix 1. Compaction process:** All mixtures were compacted under laboratory conditions. Every 40 mm layer of concrete was vibro-compacted using a vibration table for 15 seconds. A more extensive study on improving the compaction of concrete can be found in Hyde & Kinnane, (2016).

2. **Mix 2. Replacing aggregate type:** Coarse aggregate type makes up for approximately 50% of concrete constituents, so replacing limestone (typical aggregate of choice in Ireland) with the more conductive quartzite (Robertson, 1988) was expected to improve the overall conductivity.

3. **Mix 3. Improving the gradation:** Increasing the cement content increases the quantity of finer particles to fill in the voids in the concrete mixture. Increasing the cement content was an initial step, greater efforts have been made to improve the gradation in other studies by using ultra-fine pozzolanic materials such as silica fume (Hyde & Kinnane, 2016; Xu & Chung, 2000).
4. **Mix 4. Incorporating steel fibres:** Steel has a thermal conductivity of 50 W/mK, so incorporating a high proportion of steel fibres (100 kg/m$^3$) could increase the overall conductivity of the concrete. Achieving a high dosage of steel fibres is made viable by reducing the overall aggregate maximum size and incorporating super plasticiser (West et al., 2015). 35 mm length hooked end steel fibres with a 0.5 mm diameter were used.

5. **Mix 5. Incorporating scrap aluminium:** Scrap aluminium filings have the potential to increase the overall conductivity given its high conductivity of 180 W/mK. 38 kg/m$^3$ of aluminium is added, which is volumetrically equivalent to 100 kg/m$^3$ of steel (given its lower density).

For a more comprehensive study of other methods to increase the thermal conductivity of concrete, such as including magnetite and steel, readers should refer to Wadsö et al. (2012).

### 3.2.2 Concrete conductivity

The conductivity of each mixture was calculated using a quasi-steady state conductivity test method similar to the test setup outlined in Robinson et al. (2017), except with smaller concrete samples. A schematic of the set-up is presented in Figure 3.12. Four $0.2 \times 0.2 \times 0.045$ m concrete samples of each of the five trial mixtures were prepared. They were then placed in cut-outs of high performance insulation ($k_{ins} = 0.023$ W/mK). A tight fit between the concrete specimen and insulation was achieved by making the insulation cut outs smaller than required and squeezing the samples in place. The samples were heated at the back by a hot plate which was kept at a constant temperature ($50 ^\circ C$) throughout the duration of the experiment.

The constant temperature was achieved by circulating a fluid at a high enough flow rate so that the temperature difference between the inlet and outlet of the hot plate was negligible. The fluid was drawn from a 60 L insulated water tank (Figure 3.12) by a Grundfos UP 20-45 circulation pump. The tank was heated by a 3 kW electrical immersion heating element and the temperature was controlled by a technologic TDF 11PID temperature controller. When the pump was turned on the fluid was circulated through two plates with embedded channels for the fluid to pass through (heat exchangers) made from a composite of aluminium and PVC. The hot plate (as labelled in Figure 3.12) provided the heat source for the back of the concrete samples while the guard plate, in addition to a 70 mm layer of insulation, ensured that the direction of heat transfer is out of the hot plate and into the samples. The front of the samples were exposed to ambient conditions in order to achieve a temperature difference across the samples. The room was sufficiently large to allow for the assumption that it was a heat reservoir and does not heat up significantly by the hot plate system.
Four 80 mm diameter Hukseflux HFP01 heat flux sensors were used with two separate Campbell Scientific CR1000 data loggers (two sensors per data logger) to measure the heat flux. Eight Type K thermocouple sensors were used in conjunction with a National Instruments data logger to measure the temperatures. The equipment used is illustrated in Figure 3.13 which also includes a thermal image of the samples during the heating stage.

By measuring the thickness of each sample, recording the temperature at the back of the samples $T_{hot}$, the temperature at the front of the samples, $T_{cold}$, and the heat flux through the samples, $Q_{flux}$, the conductivity of each sample was calculated. For the calculations, it is assumed that the heat transfer path is one dimensional. Good contact between the insulation and edges of the samples was achieved by making the cut-outs slightly smaller than the samples and squeezing them into place to allow for the assumption that the heat transfer was one dimensional. The conductivity of each concrete sample, $k_c$, was calculated as per Eq. (3.2).

$$k_c = \frac{Q_{flux} \ t_{slice}}{T_{hot} - T_{cold}}$$  \hspace{1cm} \text{Eq. (3.2)}$$

where, $Q_{flux}$, is the heat flux through the samples, $T_{hot}$ is the temperature at the back of the collector, $T_{cold}$ is the temperature at the front of the collector and $t_{slice}$ is the thickness of the concrete samples.
Recordings were taken every minute and an example of the transient response of one of the samples is displayed in Figure 3.14.

The transient temperature response shows how the “hot side” of the concrete initially heats up dramatically and then slows down as heat is drawn through the concrete samples to the “cold side”, which in turn begins to heat up. Steady state is then achieved, after approximately 3 hours, resulting in a temperature difference and steady heat flux that can be used to calculate the thermal conductivity of each concrete specimen. The thermal response of 20 specimens was measured (5 mixtures × 4 samples of each mix). The results of which are shown in Figure 3.15. The conductivity of each mixture was calculated as the average of the four specimens. Error bars were also used to indicate the maximum and minimum conductivity values of the four samples for each mixture design.

All concrete mixtures show a higher thermal conductivity than the average conductivity value found in the literature for concrete solar collectors (≈ 1.27 W.mK). Average thermal conductivities for the trial mixtures range from 1.40 W/mK for the reference mixture to 2.06 W/mK for the concrete with steel fibres.
The aluminium reacted with the alkalis in the cement producing hydrogen gas, forming air voids in the mixture. This chemical reaction reduced the strength and overall conductivity of the concrete with scrap aluminium and was therefore omitted as a possible mixture for the concrete solar collectors.

While the concrete with steel fibres showed the highest conductivity, it exhibited very poor workability. This poor workability (even with the addition of superplasticiser) would result in a poor contact between the pipes and concrete, increasing the thermal resistance between the pipe and concrete. Also, the additional cost of the high dosage of steel fibres possibly does not warrant the improved performance of the CSC. Lastly, the fibres were not all aligned perpendicular to the pipe (ideal scenario), instead they were randomly distributed at different angles. Figure 3.16 presents the distribution of the steel
fibres in the concrete mixture. A flash was used in the camera taking the photo for optimum visual results. Given the drawbacks of concrete mixtures with high dosage steel fibres, Mix 3 (i.e. the concrete mixture with next highest thermal conductivity) was used as the recipe for the concrete used in tested CSCs.

Figure 3.16. Close-up of steel fibre distribution in concrete using quartzite (left) vs. reference mixture using limestone aggregates (right).

### 3.2.3 Concrete absorptance

A comprehensive study on reducing the solar absorptance has been conducted by Sweeney (2013) to increase surface albedo and reduce heat island effects. Sweeney (2013) outlines the real and negative implications of concrete buildings absorbing solar radiation and emitting the heat at high surface temperatures. This work, on the other hand, focuses on maximising the solar energy absorbed by the building and extracting the heat for applications in the building. For maximum solar gain, a high surface absorptance is therefore desirable. Many concrete finishes, colours, textures and mixtures exist, all of which influence the surface absorptance. A small-scale laboratory set-up is used to measure the reflectance, \( \rho \), and hence the absorptance, \( \alpha \), of eight different concrete surfaces.

All the samples are designed as per mixture 3 from Table 3.1 and include four plain concrete mixtures with no additives as well as four other concrete mixtures with different cement pigment colouring (5% added per weight of cement) namely black, red, yellow and brown. The pigments are supplied by Charles Tennant Ireland (2017). Of the four plain concrete mixtures, one was painted black, one finished with a trowel and one finished with a timber edge; the other was left unfinished. An image of each of
the eight surface finishes is displayed in Table 3.2. Three small samples \((20 \times 50 \times 50\) mm\) of each of the 8 test mixtures/finishes were cast and allowed to cure.

Table 3.2. Label and associated image for the different concrete surface finishes assessed for surface absorptance (all pigmented concretes left unfinished).

<table>
<thead>
<tr>
<th>Concrete mixture (Finish)</th>
<th>Photograph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain (Trowel finish)</td>
<td>![Image]</td>
</tr>
<tr>
<td>Plain (Timber finish)</td>
<td>![Image]</td>
</tr>
<tr>
<td>Plain (Unfinished)</td>
<td>![Image]</td>
</tr>
<tr>
<td>Black painted surface</td>
<td>![Image]</td>
</tr>
<tr>
<td>Red pigment</td>
<td>![Image]</td>
</tr>
<tr>
<td>Yellow pigment</td>
<td>![Image]</td>
</tr>
<tr>
<td>Black pigment</td>
<td>![Image]</td>
</tr>
<tr>
<td>Brown pigment</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

The reflectance of each sample was measured using an integrated sphere set-up and the absorptance subsequently calculated. A schematic of the setup is displayed in Figure 3.17.
A beam of light is passed through the integrated sphere and all other lights in the room are switched off and room is left dark. The dashed line in the schematic traces out a typical path of a light beam entering the sphere and being reflected off the concrete sample. By measuring the amount of light reflected off the sample the absorptance of that sample can be calculated ($\alpha = 1 - \rho$). The integrated sphere set-up consisted of an OceanOptics DH-2000-BAL halogen light-source connected by a fibre optic cable with a LabSphere RT-060-SF integrated sphere which in return was connected to a StellarNet Comet UV-VIS-NIR spectrometer by a fibre optic cable. These individual components are displayed in Figure 3.18.
For each sample the reflectance was measured twice following steps 1 to 5.

1. The light source was switched on and the integrated sphere was illuminated by the light beam passing through it.
2. A calibrated standard reflectance surface was placed on the sample holder at the back of the integrated sphere and the first reflectance standard reading was recorded, $S_{\text{std}}(\lambda)$.
3. The light beam was blocked and a dark reading was recorded, $S_{\text{Dark}}(\lambda)$.
4. The sample replaced the standard reflectance surface and a reading was taken, $S(\lambda)$.
5. The reflectance factor $R(\lambda)$ was recorded according to Eq. (3.3) where $R_{\text{Std}}(\lambda)$ stands for the reflectance data of the calibrated standard.

$$R(\lambda) = R_{\text{Std}}(\lambda) \left( \frac{S_S(\lambda) - S_{\text{Dark}}(\lambda)}{S_{\text{std}}(\lambda) - S_{\text{Dark}}(\lambda)} \right)$$  \quad \text{Eq. (3.3)}

For each of the eight surface finishes six plots of reflectance vs wavelength were generated i.e. two tests of each of the three samples (a total of 48 tests, 8 surfaces $\times$ 3 samples $\times$ 2 tests). An example of the variance in the black painted samples is displayed in Figure 3.19.

![Figure 3.19. Variation between samples and tests for the reflectance as a function of the wavelength for the black painted concrete surface.](image)

The average of the six sample tests was taken for each surface finish. A comparison of the reflectance for each surface finish is displayed in Figure 3.20. The darker colours are characterised by the lower reflectance. No significant difference between the two surface finishes is observed with the plain unfinished concrete displaying a slightly higher reflectance in the UV range. The solar absorptance was
subsequently calculated within only the UV and Visible wavelength ranges. The infrared reflectance was not obtainable with the given equipment and the results were extrapolated assuming the value at 900nm as a constant to account for the remaining portion of the solar spectrum and the solar absorptance, $\alpha_s$, was calculated according to Eq. (3.4). For spectrally selective coatings an infrared spectrophotometer would also be required. R($\lambda$) is the wavelength specific reflectance and $I_s$($\lambda$) is the wavelength specific radiation for Air Mass 1.5 electromagnetic radiation (AM 1.5). The absorptance of each concrete surface finish is presented in Table 3.3.

$$\alpha_s = \frac{\int_{0.3}^{0.9} (1 - R(\lambda))I_s(\lambda)d\lambda}{\int_{0.3}^{0.9} I_s(\lambda)d\lambda} \quad \text{Eq. (3.4)}$$

![Figure 3.20. Spectral reflectivity of concrete surface finishes and electromagnetic spectrum.](image)

As expected the darker colours have a higher absorptance and are therefore more suitable for concrete solar collectors. No significant difference was found between the plain concrete mixtures with different surface finishes. The greatest variance was found for the lighter coloured concrete. At a closer inspection, a more inhomogeneous colour was found on the lighter coloured surfaces when compared with the darker colours, possibly attributed to this greater variance.
Table 3.3. Concrete finish and associated absorptance and variance between the different samples.

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>Absorptance ± Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain (Trowel finish)</td>
<td>0.69 ± 0.023</td>
</tr>
<tr>
<td>Plain (Timber finish)</td>
<td>0.69 ± 0.024</td>
</tr>
<tr>
<td>Plain (Unfinished)</td>
<td>0.7 ± 0.019</td>
</tr>
<tr>
<td>Black painted surface</td>
<td>0.94 ± 0.002</td>
</tr>
<tr>
<td>Red pigment</td>
<td>0.83 ± 0.022</td>
</tr>
<tr>
<td>Yellow pigment</td>
<td>0.67 ± 0.04</td>
</tr>
<tr>
<td>Black pigment</td>
<td>0.89 ± 0.004</td>
</tr>
<tr>
<td>Brown pigment</td>
<td>0.85 ± 0.01</td>
</tr>
</tbody>
</table>

3.2.4 Other concrete properties

While concrete conductivity and surface absorptance were of primary concern for the CSCs, other standard concrete properties were recorded. These properties are outlined in this section.

3.2.4.1 Compressive strength

Three 100 mm cubes were produced in the same batch of concrete for the mixtures prepared for conductivity testing. After 28 days the concrete cubes were taken out of the curing tank. Two cubes of each mixture were tested for their compressive strength using the apparatus presented in Figure 3.21. The remaining third cube was left and tested after being there for a year. The compressive strength test results are displayed in Figure 3.22.

Figure 3.21. Concrete cube strength testing apparatus.
The concrete with steel fibres and the concrete with added cement exhibit the greatest compressive strengths. No significant difference between the reference concrete mixture and the mixture with quartzite was observed for the 28\textsuperscript{th} day strength. A slight increase was noted after 1 year for the concrete with quartzite. But given the fact that only one sample was used of each, no reasonable conclusion can be made that there is any significant increase in the strength by replacing quartzite. It can however be concluded that there is no significant loss of strength if quartzite was to be used in place of limestone. The concrete incorporating aluminium produces an extremely weak mixture that in fact degrades over time and should never be used as a structural material.

### 3.2.4.2 Moisture content

The surface moisture content of each sample was measured weekly to identify when most of the drying was complete. The results for the first 5 weeks are plotted in Figure 3.23.
Over time the concrete specimens dry out, with no significant change in moisture content observed after 4 weeks. It can be assumed that when the concrete samples were tested for conductivity, they were completely dry, as they were tested six months after curing.

3.2.4.3 Density

The density of each mixture was measured immediately after curing and again after 5 weeks. The results are displayed in Figure 3.24.

![Figure 3.24. Concrete wet and dry density for the different concrete mixtures.](image)

Like the strength measurements, no significant difference was observed between the Reference and Quartzite mixture. The concrete with steel fibres displayed the highest density and the high cement concrete displayed higher dry density, both as expected. The concrete with aluminium displayed a significantly lower density than the other four mixtures due to additional voids in the concrete.

3.3 Modelling software

A number of different software packages were used in this work. However, the two key programs used were “LabVIEW” for logging the performance of the experimental concrete solar collector set-up and “COMSOL Multiphysics” for modelling the thermal behaviour of the concrete solar collectors. The in-depth description of the modelling technique used is not presented in this chapter, both the 2D and 3D models are presented in Chapter 5 and 6 respectively. Both models were, however, implemented in COMSOL Multiphysics.
3.3.1 LabVIEW

LabVIEW, as described by the National Instruments website (LabVIEW, 2017), is a systems engineering software for applications that need testing, measurement and control with rapid access to hardware and data. It was used in this study for data acquisition and calibration (as discussed in Section 3.1.3.2). The data acquisition program used in this study for temperature, irradiance and flow measurements is graphically displayed in Figure 3.25.

![LabVIEW Interface](image)

Figure 3.25. Labview interface. Data acquisition program (right) and graphical interface (left).

The core of the program was built in the “DAQ Assistant module” which is where sensors were added, calibrated and sample rates were specified. Information was passed to a chart to allow for real time visualization of the recordings and to a measurement file which recorded the numeric values of the associated sensors. The time of each measurement was extracted from the host operating system (in this case Windows 7) and was appended to the relevant row of numerical readings. The program was contained within a loop controlled by a boolean switch which can manually be turned on or off; the program ran and recorded continuously until this switch is turned off. The computer used, which is housed in the attic of the Simon Perry building, was not connected to the network and an alert system was therefore not included. This resulted in some days where data was not recorded throughout the year due to power cuts and other unforeseen events.

3.3.2 COMSOL Multiphysics

COMSOL Multiphysics is a sophisticated Finite Element Analysis (FEA) software that is used to simulate complex 1D, 2D and 3D physics and multi-physics problems for both academic and commercial purposes. It only uses the finite element method to solve problems and is therefore a
specialist in computing multi-physics problems efficiently. The graphical interface of an example of a COMSOL Model is displayed in Figure 3.26.

![COMSOL Model Interface](image)

Figure 3.26. COMSOL Multiphysics user interface.

The complexity of a given model varies significantly and the details of the concrete solar collector model used in this study is discussed in greater depths in a later section. The typical steps used in any COMSOL Multiphysics model are outlined below:

1. The geometry is defined, be it 1D, 2D or, in the case of Figure 3.26, 3D. CAD geometries can be created within the software or imported from a third-party software (e.g. AutoDesk Inventor or SolidWorks).
2. The materials and their relevant properties are defined and assigned to the relevant geometry sections.
3. Boundary and initial conditions are assigned to the relevant areas of the geometry; these may be steady state or time dependent.
4. A finite element mesh is generated which divides the entire geometric domain into several smaller domains (or elements). The size and number of elements depends on the physical problem and desired accuracy. While default geometries can be applied that use built-in algorithms to determine the size and distribution of the mesh a better approach would be to apply a user-defined mesh. Defining the mesh requires both proficiency with the simulation tool as well as a good understanding of the physical problem. This can result in computationally
efficient meshes by applying smaller elements in areas where big differences of the dependent variable are expected (for example temperature in heat transfer problems).

5. The type of study is setup e.g. steady state or time dependent. The time step, solver and tolerance can also be set in this module. In this instance, it is advisable to use COMSOL’s built-in algorithm to select the most appropriate solver type.

Finally, the post processing is carried out. A plethora of geometric displays and graphics are achievable, which is one of the significant advantages of COMSOL Multiphysics.

3.4 Conclusion for Chapter 3

A description of the materials and methods that define this research has been presented in this chapter. A summary of the proposed Concrete Solar Collector’s (CSC) experimental set-up is first presented. Following on from this an in-depth description of the design, fabrication and installation of the experimental set-up is presented in Section 3.1. The performance properties of concern for the concrete are investigated in Section 3.2. Lastly, an overview of the software used in this work is outlined in Section 3.3.
Chapter 4

Performance Evaluation of a Concrete Solar Collector
4 Performance Evaluation of a Concrete Solar Collector

This chapter begins by outlining the performance indicators which are used to assess the Concrete Solar Collector’s (CSC) performance (Section 4.1). In Section 4.2 the seasonal performance of the CSC system is then presented for individual days as well as a collective run of days. The thermal performance of the system is investigated in detail in Section 4.3 for a period of six reference days in March 2017 (25th to the 30th) which includes both clear and cloudy conditions. Section 4.4 then investigates individual changes made to the system, e.g. insulation at the back, tank volume and flow rate. Simulation studies are used in the subsequent chapters to build upon the knowledge gained from this experimental investigation chapter. The performance of the CSC system is subject to the parameters summarised in Table 4.1, unless explicitly mentioned in the associated text.

4.1 Performance indicators and uncertainty

The performance of the CSCs is based on the fluid temperatures and associated mass flow rate measurements. The energy can be calculated based on fluid temperatures in the collector at discrete time steps; or based on temperature recordings of the tank throughout the day. Both energy calculations are used and explained in this section.

4.1.1 Energy from collectors and daily efficiency

The energy calculated from the collectors at discrete times is given by Eq. (4.1).

\[ Q_u = \dot{m}c_w(T_o - T_i) \]

Eq. (4.1)

which is based on the temperature difference between the inlet, \( T_i \), and the outlet, \( T_o \), of the CSC, the mass flow rate, \( \dot{m} \), and the specific heat capacity of the heat transfer fluid, in this case water, \( c_w \). The useful rate of energy, \( Q_u \), is calculated at five minute time intervals in the experimental set-up. The useful energy output per day, \( Q_{u,d} \), is calculated by converting these energy rate quantities, \( Q_u \) (W), at 5 minute intervals into averaged energy quantities (kWh) and summing the values over a period of a day.

The flow rate measurements, along with the temperature measurements, are used to calculate the energy output from the CSCs. The daily energy output can be used to calculate the daily efficiency, \( \eta_d \), according to Eq. (4.2).

\[ \eta_d = \frac{Q_{u,d}}{I_d} \]

Eq. (4.2)
Table 4.1: Summary of concrete solar collector material properties and geometric dimensions.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter, symbol (Unit)</th>
<th>Value</th>
<th>Comment on parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Parameters</td>
<td>Concrete conductivity, $k_c$ (W/mK)</td>
<td>1.76</td>
<td>Experimentally measured</td>
</tr>
<tr>
<td></td>
<td>Concrete heat capacity, $C_c$ (J/kgK)</td>
<td>800</td>
<td>Average value from the CSC literature</td>
</tr>
<tr>
<td></td>
<td>Pipe conductivity, $k_p$ (W/mK)</td>
<td>380</td>
<td>Taken from (BS ISO 10456, 2009)</td>
</tr>
<tr>
<td>Geometric Parameters</td>
<td>Pipe Diameter, $D_i$ (m)</td>
<td>0.015</td>
<td>Practical estimate</td>
</tr>
<tr>
<td></td>
<td>Pipe plane depth, $D_{plane}$ (m)</td>
<td>0.02</td>
<td>Practical estimate</td>
</tr>
<tr>
<td></td>
<td>Pipe Spacing, $D_s$ (m)</td>
<td>0.05</td>
<td>Maximizing heat exchange area</td>
</tr>
<tr>
<td></td>
<td>Panel thickness, $\delta$ (m)</td>
<td>0.08</td>
<td>Typical thickness of single skin concrete facade elements</td>
</tr>
<tr>
<td>Surface properties</td>
<td>Absorptance, $\alpha$</td>
<td>0.94</td>
<td>Experimentally measured</td>
</tr>
<tr>
<td></td>
<td>Emittance, $\varepsilon$</td>
<td>0.9</td>
<td>Common value used in the literature</td>
</tr>
<tr>
<td>Fluid</td>
<td>Mass flow rate, $\dot{m}$ (kg/s)</td>
<td>variable</td>
<td>Low flow system considered for this study</td>
</tr>
<tr>
<td></td>
<td>Fluid type</td>
<td>Water</td>
<td>Cheap, abundant and good thermal properties</td>
</tr>
<tr>
<td>Constant Geometric parameters</td>
<td>Pipe layout</td>
<td>serpentine</td>
<td>Ease of manufacture both plastic and metal/ uniform flow</td>
</tr>
<tr>
<td></td>
<td>Panel area, $A$ (m$^2$)</td>
<td>1</td>
<td>Three small solar collectors</td>
</tr>
<tr>
<td>Tank</td>
<td>Volume (m$^3$)</td>
<td>0.065</td>
<td>Approximate amount of hot water consumed by a single person per day</td>
</tr>
<tr>
<td></td>
<td>Insulation conductivity (W/mK)</td>
<td>0.03</td>
<td>Insulation specification</td>
</tr>
<tr>
<td></td>
<td>Insulation thickness (m)</td>
<td>0.025</td>
<td>Prefabricated thickness</td>
</tr>
<tr>
<td>Connecting pipes</td>
<td>Material</td>
<td>Plastic</td>
<td>Flexible and easy to construct</td>
</tr>
<tr>
<td></td>
<td>Pipe insulation (W/mK)</td>
<td>0.034</td>
<td>Insulation specification</td>
</tr>
<tr>
<td></td>
<td>Pipe insulation thickness (m)</td>
<td>0.02</td>
<td>Practical estimate</td>
</tr>
<tr>
<td></td>
<td>Surface finish</td>
<td>Reflective foil</td>
<td>Minimize heat gain</td>
</tr>
</tbody>
</table>
where \( I_d \) is the total solar radiation (kWh) incident on the surface for a day. The daily efficiency provides a good indication of the CSC’s performance on days with solar radiation, but on cloudy days high efficiencies over 100% may be observed because the ambient air is heating the collectors above the water mains temperature, producing a small energy output which is greater than the available solar energy for that day. So, the daily efficiency is only referred to in this work for the analysis of individual days with sufficient solar radiation.

4.1.2 Energy from the system and solar fraction

The energy added to the tank is provided from the collectors, however, some losses and gains occur in the pipes connecting the tank to the collectors. Hence a different performance indicator is assigned to the energy output of the system, \( Q_{u,sys} \). The daily energy gain of the CSC system, \( Q_{u,sys} \), is estimated based on tank temperature measurements and is calculated according to Eq. (4.3).

\[
Q_{u,sys} = m_{tank} c_f (T_{tank,max} - T_{tank,min})
\]

Eq. (4.3)

where \( m_{tank} \) is the mass of water in the storage tank. Tank temperatures, \( T_{tank} \), are based on the average of the three thermocouple measurements located in the tank (as displayed in Figure 3.2). \( T_{tank,max} \) is the maximum tank temperature achieved for a given day and \( T_{tank,min} \) is the minimum tank temperature that morning. The minimum tank temperature approximates the water mains temperature. The maximum and minimum tank temperatures are displayed in Figure 4.1.

![Figure 4.1. Example of tank temperature throughout a sample day.](image-url)
Within the solar thermal literature, the Solar Fraction (SF) is often used as a system performance indicator. The SF is the energy supplied by the CSC system divided by the total amount of energy used, $Q_{load}$, for a given hot water application as per Eq. (4.4).

$$SF = \frac{Q_{u,sys}}{Q_{load}}$$  Eq. (4.4)

Since the SF depends on the hot water load and since the installed system does not have a hot water draw off incorporated into the system a theoretical hot water draw off is instead considered. This is done by assuming a single draw off every evening after the tank has reached its max temperature. While not entirely representative of a real system, this robust method allows for the analysis of individual days. In later chapter real hot water draw off profiles are considered using modelling techniques. The daily hot water load, $Q_{load}$, is approximated per Eq. (4.5).

$$Q_{load} = m_{load}c_f(T_{app} - T_{tank,min})$$  Eq. (4.5)

$m_{load}$ is the mass of water assumed to be consumed every evening. It is assumed that this small system is installed for a single-occupant apartment and that 54 litres of hot water (NSAI S.R. 50-2, 2012) is consumed in the evening at an application temperature, $T_{app}$, of 52°C (Energy Saving Trust, 2008). Following Eq 4.5, this equates to a hot water energy requirement of approximately 2.6 kWh/day. The difference between the total energy used and the energy supplied by the CSC system is the auxiliary heating requirement, $Q_{aux}$, which is supplied by an auxiliary source (e.g. oil, gas or electricity).

### 4.1.3 Uncertainty

The accumulated uncertainty of each performance indicator is calculated using the Root Sum Square (RSS) method (also used by Robinson et al. (2017)) is outlined in Eq. (4.6).

$$u_y = \sqrt{\left(\frac{\partial y}{\partial x_1}u_{x1}\right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n}u_{xn}\right)^2}$$  Eq. (4.6)

where the overall uncertainty, $u_y$, of each performance indicator, $y$ (e.g. $Q_{aux}$ and $Q_{u,sys}$), is calculated based on the individual errors, $u_x$, of the measured parameters, $x$ (e.g $T_{tank,min}$, $T_{tank,max}$, $m_{tank}$ and $\dot{m}$). These individual uncertainties of all measured values are documented in Table 4.2. The accumulated errors are documented in the following sections which assess the seasonal energy performance of the CSCs.
Table 4.2. Measured inputs, instrumentation used and associated accuracy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrumentation</th>
<th>Model/type</th>
<th>Uncertainty/Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance, $G$ (W/m$^2$)</td>
<td>Pyranometer</td>
<td>Kipp &amp; Zonen CMP 11</td>
<td>&lt; 5.25%</td>
</tr>
<tr>
<td>Average Wind speed, $u_w$ (m/s)</td>
<td>Anemometer</td>
<td>Young 05103</td>
<td>± 0.3 m/s</td>
</tr>
<tr>
<td>Ambient temperature, $T_a$ ($^{\circ}$C)</td>
<td>Thermocouple</td>
<td>Type K</td>
<td>± 0.05 K</td>
</tr>
<tr>
<td>Flow rate, $\dot{m}$ (kg/s)</td>
<td>Magnetic induced flow meter</td>
<td>IFM SM8000</td>
<td>± 0.0022 kg/s</td>
</tr>
<tr>
<td>Concrete thermal conductivity, $k_c$ (W/mK)</td>
<td>Hot plate test</td>
<td>NA</td>
<td>± 0.18 W/mK</td>
</tr>
<tr>
<td>Concrete density, $\rho_c$ (kg/m$^3$)</td>
<td>Weight in water &amp; air</td>
<td>NA</td>
<td>± 10 kg/m$^3$</td>
</tr>
<tr>
<td>solar absorptance, $\alpha$</td>
<td>Integrated Sphere</td>
<td>NA</td>
<td>± 0.02</td>
</tr>
</tbody>
</table>

4.1.4 Limitations of classical performance indicators

It has been correctly highlighted throughout the CSC literature that instantaneous Hotell Whillier Bliss (HWB) efficiency curves are not applicable when assessing the performance of CSCs and other solar collectors with non-negligible heat capacities. It is interesting, however, to analyse what these curves show for a CSC. The HWB curves, which are typically used to assess the performance of standard solar thermal collectors (e.g. FPC, ETC, UC), compare the instantaneous efficiency, $\eta_i$, with the reduced temperature difference ($\Delta T/G$). The instantaneous efficiency is calculated according to Eq. (4.7).

$$\eta_i = \frac{\dot{Q}_u}{G}$$

Eq. (4.7)

$G$ is the irradiance in W/m$^2$. $\Delta T$, the temperature difference, may be the difference between the inlet temperature, $T_i$, and the ambient temperature, $T_a$ (ASHRAE 93-2010, 2014) or between the mean fluid temperature and the ambient temperature (BS EN ISO 9806, 2013). The results presented in Figure 4.3 apply the ASHRAE method to give a direct comparison with those results of Kim & Kim (2012), whose results for both glazed and unglazed solar thermal collectors are presented in Figure 4.2. The figures highlight the difference between the CSC (which has significant thermal mass) and the other two collectors (with negligible thermal mass).
A linear correlation between the reduced temperature difference and the instantaneous efficiency is not apparent for the CSC. Instead there appears to be three primary performance stages (circled and colour coded in Figure 4.3). In the morning, as the sun begins to heat the collector, a particularly poor performance is observed. This is due to the thermal mass temporarily storing the solar energy. Later in the afternoon (at approximately 12:00 midday for the 25th of March) the efficiency becomes relatively constant across the reduced temperature difference circled in Figure 4.3, as some of the stored energy in the concrete begins to be extracted by the pipes. Then later in the early evening when the available solar radiation is lower, the efficiency improves at greater temperature differences, this is because the heat stored in the concrete is being released and extracted by the embedded pipe. It is therefore evident
that assuming a linear fit between the instantaneous efficiency and reduced temperature difference would be meaningless.

To overcome the non-negligible heat capacitance effects, authors of research on Integrated Collector/Storage Solar Water Heaters (ICSSWH) use average values taken during the heat up phase and produce efficiency curves similar to the standard HWB curves except using average values over the day (Smyth et al., 2004; Tripanagnostopoulos & Yianoulis, 1992). An ICSSWH and associated efficiency curve are presented in Figure 4.4.

Figure 4.4. (a) Image of an ICSSWH and (b) associated daily collector efficiency curve (Smyth et al., 2004).

These resulting efficiency curves used by Smyth et al. (2004) are based on the temperature difference, $\Delta T$, which is the difference between the daily average storage tank temperature, $T_{tank,ave}$, and the average ambient temperature, $T_{a,ave}$, during the heat up phase of the day.

$$T_{tank,ave} = \frac{T_{tank,max} + T_{tank,min}}{2}$$

Eq. (4.8)

where $T_{tank,max}$ and $T_{tank,min}$ are the average tank temperatures of the tank at the end and start of the heat up period of the day respectively. The average solar irradiance, $I_{ave}$, is given by Eq. (4.9)
\[ I_{ave} = \frac{\int_{t_{start}}^{t_{end}} I_d(t) \, dt}{\Delta t} \quad \text{Eq. (4.9)} \]

where \( t_{end} \) and \( t_{start} \) are the times of maximum and minimum tank temperatures respectively. \( \Delta t \) is the time difference between \( t_{end} \) and \( t_{start} \) and \( I_d \) is the solar irradiance. The collector efficiency, \( \eta_{col} \), is calculated as per Eq. (4.2), except the energy rate values are summated for the heat up phase of the day only. The method worked well for the ICSSWH producing an \( r^2 \) value of 0.65. For the CSC system considered in this study the relationship, obtained using this method, is shown in Figure 4.5.

![Graph showing daily efficiency curve for the concrete sola collector](image)

**Figure 4.5.** Daily efficiency curve for the concrete sola collector

The performance of the CSC and the coefficient of determination are notably worse than that of the ICSSWH. This may be attributed to the unglazed nature of the CSCs. Because a strong relationship between efficiency and reduced temperature difference was not obtained this method does not provide a satisfactory representation of the CSCs performance. To understand the CSCs further the seasonal performance is analysed in greater detail in subsequent sections.

### 4.2 Seasonal performance

The performance of the CSC system is assessed in this study with reference to individual days of each of the four seasons in Dublin. First individual daily temperature profiles for three selected days from each season, namely a clear day, a cloudy day and an average day were generated. The average day is selected based on the day with a total radiation closest to the average for that month. The daily energy output from the system and the collector were subsequently presented to determine the performance of the system over a year in Dublin.
4.2.1 Daily profiles

The daily temperature and irradiance profiles for the clear, cloudy and average days are presented in chronological order from when the testing began. These three days were used to show how the CSC collector performed under ideal conditions as well as average and poor conditions. The results for October 2016 are presented first (Figure 4.6), followed by the results for December (Figure 4.7), then the results for March (Figure 4.8) and finally the results for July (Figure 4.9).

The first notable result from the clear day for each season is that the summer months display the lowest peak solar irradiance (Figure 4.9). However, solar irradiance in the summer is present for a longer duration (i.e. the wider irradiance curve) and the ambient temperature is higher. The lower peak irradiance is directly due to the angle of inclination of the CSCs, which in this case is vertical. Because the sun is higher in the sky at solar noon in summer, the angle between the normal to the absorbing surface and the direct irradiance is lower than it is in winter, spring and autumn months. A maximum daily solar irradiance of between 600 – 700 W/m² is observed for spring and autumn months. Unlike tilted solar collectors, and even more so horizontally installed solar collectors, vertically installed solar collectors, such as façade integrated solar thermal technologies, do not experience great differences in the seasonal energy gains. On each of the clear days from all four months the outlet temperature reaches a peak temperature of more than 14 °C higher than the outside ambient temperature. In winter the temperature difference between air temperature and outlet temperature (16 °C) is greater than for summer (14.5 °C). The greatest difference throughout the year occurs in spring (18.4 °C).

Of more importance than the time of year is the cloud cover. A CSC on an average day in summer (Figure 4.9) was outperformed by a completely clear day in winter (Figure 4.7). On the cloudy days for each season it is clear from all the figures that the outlet and inlet fluid temperature in the CSCs were dictated by both the ambient outdoor and indoor temperature. On the cloudy day in autumn (Figure 4.6) the diffuse radiation results in a small increase in the fluid outlet temperature during the day. On the particularly cloudy day in winter (Figure 4.7), with almost no diffuse radiation, no noticeable increase in the fluid temperatures was found during the day. On some of the days with low solar radiation (e.g. Oct 28) a small increase in performance is observed; this increase in performance is attributed to the increase in ambient temperature.
Figure 4.6. Daily temperature and irradiance profiles for a clear, average and cloudy day in autumn (October 2016).

Figure 4.7. Daily temperature and irradiance profiles for a clear, average and cloudy day in winter (December 2016).
Figure 4.8. Daily temperature and irradiance profiles for a clear, average and cloudy day in spring (March 2017).

Figure 4.9. Daily temperature and irradiance profiles for a clear, average and cloudy day in summer (July 2017).
4.2.2 Energy output

All recorded days for each of the sample months are presented in this section in relation to the daily energy output directly from the CSC, $Q_{u,d}$, and accumulated throughout the day in the tank, $Q_{u,sys}$. The daily energy outputs and the average energy outputs for each month are presented in Figure 4.10. The average values are based on the values for those measured days shown in the figure. A clear relationship between the amount of solar radiation and the energy output is highlighted. The relatively small variation in energy output throughout the year is contrary to the typical tilted roof attached solar thermal system, which experiences much greater energy outputs in the summer than winter. Again, this is attributed to the vertical orientation of the concrete solar collectors.

The winter month displayed the lowest energy output throughout the year but worthwhile energy savings can still be made on clear days. On average, the summer month had the greatest energy output, attributed to the fact there are a greater number of clear days in the summer and the longer hours of daylight. In fact, individual days in autumn and spring months produced the greatest energy outputs and solar radiation. Also, in the summer months, some days with low levels of solar radiation resulted in energy outputs due an increase in the ambient temperature during the day.

Considering the SF of each month, a maximum SF of 42% was recorded in spring (March 15th) and summer (July 17th) months with SF as low as almost 0% recorded on a number of cloudy days in winter. The average energy output from the system over the four months was 0.65 kWh/day, which equates to a solar fraction of 25% per year for a 2.6 kWh hot water demand. This value reduced to 23.8% when the electrical energy used by a pump was considered. This pumping power was based on theoretical calculations of a pump running continuously for a duration of $\Delta t_{\text{max-min}}$ at a power of 4.5 W, calculated based on pressure measurements taken from the system as well as an assumed operation efficiency of 10%. $\Delta t_{\text{max-min}}$ is the time between the occurrence of the minimum and maximum tank temperatures. The mechanical performance of the pump is investigated further in Section 4.3.5.

The error bars, which are based on calculations from Eq. (4.6), show a slightly greater uncertainty with the measurement of the energy collected from the collectors compared with the tank. This is attributed to the greater uncertainty of the mass flow rate measurement (kg/s) compared with the uncertainty of the measurement of the mass of the fluid in the tank (kg). The difference in energy from the collectors and from the system is attributed to the heat gained/lost by the connecting pipes.
Figure 4.10. Seasonal energy output directly from the collector, $Q_{ud}$ (Eq. (4.1)), and accumulated throughout the day in the tank, $Q_{sys}$ (Eq. (4.3)).
The relationship between the energy output from the collectors (kWh) and the solar radiation for individual days is presented in Figure 4.11.

![Figure 4.11. Daily energy collected from the collected against the daily solar radiation available.](image)

Each data point represents a day from the four sample months. A total of 95 days are presented. A linear relationship between the energy output and available solar energy is displayed with a coefficient of determination (R$^2$) value of 0.88. A simple method of predicting the performance of the CSC on a given day is to use Eq. (4.3) which is calculated based on the linear relationship found in Figure 4.11.

\[ Q_{u,d} = 0.45(I_d) - 0.13 \]  

Eq. (4.10)

The equation shows that there is no useful energy to be gained on days with daily solar radiation lower than 0.13 kWh/day. As a result of the variance in the data it is evident that there are other parameters that effect the performance, a more in-depth description of these influential parameters is provided in Chapter 5 when the CSCs are modelled using finite element techniques.

### 4.3 System detailed performance

Six reference days are used in this section to understand and describe the operation of the system in detail. The locations of the individual thermocouples are presented in the schematic of the system in Chapter 3 (Figure 3.2). The reference days discussed in this section include three clear days (25th to 27th) as well as three partially cloudy and cloudy days (28th to 30th). Graphical representation of the performance over one day is visually easier to analyse than six consecutive days; so, for the analysis of just one day the 25th of March is used. A consistent plot style is used for each measurement (e.g. a dark red continuous line is used for indoor ambient temperature measurements).
4.3.1 Weather

The weather conditions for the reference six days in March are presented in Figure 4.12. The irradiance, wind speed and outside ambient temperature influence the performance of the CSC. The inside ambient temperature influences the heat lost from the storage tank.

![Figure 4.12. Weather conditions and tank temperature from March 25th to March 30th in Dublin, Ireland.](image)

The indoor ambient temperature has afternoon peaks slightly after the outdoor temperature measurement and with a consistently smoother and higher temperature. Since the CSCs were located outdoors they were influenced by the fluctuating outdoor ambient temperatures. The CSCs were located in a relatively calm environment with no strong prevailing winds, as noted by the wind speed plot in Figure 4.12. The wind speed was recorded as the average wind speed over a ten-minute period. Of most importance to the performance of the CSCs is the solar irradiance. The irradiance for March peaks at around 650 W/m². Perfectly smooth sinusoidal irradiance curves are rarely obtained in Ireland given the persistent clouds throughout the year. Instead clear days are represented by curves like those of March 25th – 27th. The days of March 28th – 30th are representative of partially cloudy and cloudy days.

The storage tank temperature was taken as the average of the three tank temperature measurements (Figure 3.2). The storage tank temperature reached a maximum of 33 °C during the six reference days. The tank, which is heated by the CSCs had temperatures of approximately 20 °C higher than the outside ambient temperature on clear days in March. It is evident from these results that the CSCs were heating the storage tank. Small energy gains were also evident on cloudy days with the diffuse solar radiation increasing the temperature of the tank by approximately 3 °C from the ambient temperature. For a
system operating with a low efficiency pump, the 3 °C preheating temperature difference on cloudy days would not warrant the energy cost of running the pump.

4.3.2 Tank temperatures

The temperature of the tank depends on the CSCs temperature. Water leaves the tank and returns with thermal energy extracted from the CSCs. The cycle is repeated throughout the day with the tank gaining more and more energy and thus increasing in temperature. At a point in the day (typically afternoon on a clear day) the tank temperature reached a temperature such that the water entering the collectors no longer gains any more energy and because the pump is left running the tank begins to lose energy. At this time in a real user operated system the pump should be turned off. However, for the sake of this work the pump was left on continuously to cool down the tank overnight. This brought the tank temperature down to approximately that of mains water temperature while maintaining a mass balance, allowing for the analysis of individual days.

Plotting the temperatures at the different locations in the tank for the 25th of March (Figure 4.12) revealed a small temperature difference within the tank. The tank temperature at the top had the most notable deviation from the mean, which can be attributed to the returning fluid entering the tank here. The centre of the tank stayed the warmest when the CSCs were not gaining any additional heat. This is most likely due to the top and bottom of the tank losing heat to the indoor ambient air.

![Figure 4.13. Tank temperatures on the 25th of March 2017.](image)
Over the course of the six days the average difference across any of the tank temperatures was less than 1 °C. Figure 4.13 displays some small temperature differences within the tank but given the geometry of the tank, and the mixing induced by the water returning into the tank, it can be assumed for modelling purposes that the thermal stratification in the tank was negligible.

Thermal stratification would be a desirable condition that would result in water from the bottom of the tank entering the CSCs at a lower temperature than the average tank temperature and the water drawn-off from the top of the tank for domestic use would be at a higher temperature than the average tank temperature. Since both resulting outcomes are beneficial, thermal stratification would have resulted in an overall more efficient operation. The negligible thermal stratification in this system does however allow for the assumption that the tank was fully mixed, simplifying the mathematical modelling of the system in Chapter 5.

4.3.3 Fluid temperatures

The fluid temperatures on the 25th of March are displayed in Figure 4.14 (for the locations of each temperature sensors see Figure 3.2 in Chapter 3).

![Temperature Chart](image)

Figure 4.14. Fluid temperatures for the CSC experimental set-up on the 25th of March.

When the CSCs are heating up (between approximately 10:00 and 17:00) it is clear from Figure 4.14 that the temperature of CSC 3 was the highest (where CSC 1 was the first collector the fluid passes
The difference between the tank outlet and the inlet to the collectors was greater as the temperature increased. This was due to heat loss from the pipes connecting the tank to the CSCs. There was also heat loss from the pipes connecting the outlet of the CSCs to the tank. While efforts were made to minimise these heat losses some notable heat losses still existed. Additionally, there was some heat gain from the pipes during the mornings when the pipes were in the sunlight but the front face of the vertically installed CSCs were not. This influence was reduced by covering the insulated pipes in a reflective foil (as seen in Figure 3.3 from Chapter 3).

The greatest temperature difference was observed between the inlet and outlet of the CSC 1. This was due to the lower inlet temperature. As the inlet temperature increased, the temperature difference between the collector and the ambient increased which resulted in greater heat losses and therefore a lower efficiency. This is illustrated in Figure 4.15.

![Figure 4.15. Temperature difference between inlet and outlet of each collector for 25\textsuperscript{th} of March.](image)

In the early morning, a positive temperature difference was achieved in CSC 1. But for the same time the conditions were such that the temperature of the fluid entering CSC 2 (which is the outlet...
temperature of CSC 1) did not gain any additional heat. It was not until later in the day that the additional area of CSCs became useful as more solar radiation was captured and used as useful heat.

4.3.4 Surface temperatures

The surface of the CSCs was heated by solar radiation incident on the surface. Some of the heat from the surface of the CSCs was lost to the environment, the rest was conducted through the concrete and extracted from the embedded pipe. The average front centre and back centre surface temperatures of the CSCs are displayed in Figure 4.16. The outlet temperature (i.e. the hottest fluid temperature) in the collector is also displayed. It is clear from the figure that the fluid temperature does not reach the temperature of the surface. This is because some of the heat was lost to the environment before it could be usefully extracted from the fluid. The back surface of the concrete absorber shows a smoother curve than the front of the collector because the back of the CSCs were insulated and therefore not directly exposed to the constantly fluctuating external weather conditions (e.g. wind and irradiance). There is a short period of time just before 18:00 and after the peak fluid temperatures when the fluid temperature is hotter than the surface, this is attributed to the energy stored in the concrete.

![Figure 4.16. Average front centre and back centre surface temperatures for the 25th of March.](image)

Mar 25 00:00 06:00 12:00 18:00 00:00 Mar 26

- Front surface average (°C)
- Back surface average (°C)
- Collector 3 outlet temperature (°C)
The front surface reacts to the changing environmental conditions at a quicker rate than the fluid temperatures or back temperatures. During the heat-up phase (i.e. morning to late-afternoon) the surface temperatures of the first CSC were lower than the following CSCs. During the cool down this was reversed. As with the fluid temperature readings, front and back surface temperatures of each collector display a similar performance in Figure 4.17, with CSC 3 reaching the highest temperatures.

The data logger had a limited number of thermocouple channels which were taken up by surface, fluid, tank and ambient temperature readings. To investigate the thermal contours within the CSC simulation, finite element methods were used as detailed in Chapter 5.

4.3.5 Mechanical performance

The system hydraulics and pumping is discussed here. For this experimental set-up, a pump with adjustable flow rates was installed. This subsection investigates the energy required to circulate fluid around this system based on 1) a completely theoretical model 2) pressure measurements in the system with assumed pump performance specifications and 3) the actual power consumed by the pump measured at the power supply. The energy used by the pump is used in subsequent sections that estimate the thermal energy output of the CSC.
4.3.5.1 Flow rate

For the reference six days the flow rate was set to 0.02 kg/s. The electronic logging equipment for the flow meter had a specified sensitivity of ± 0.0005 kg/s.

![Graph showing measured flow rate vs smoothed flow rate and associated uncertainty.]

Figure 4.18. Measured flow rate vs smoothed flow rate and associated uncertainty.

However, when measured over a 10-day period for flow rates between 0.025 and 0.005 kg/s, greater sensitivities in the flow measurements were observed. The uncertainty of the flow rate measurement was taken as ± two standard deviations from a 2-hour average flow. The results for a sample of 10 days are shown in Figure 4.18. The changes in flow rates on these particular days are attributed to a combination of a poor quality pump and potential air in the system.

4.3.5.2 Theoretical pumping power

The electrical power consumed by the circulation pump, \( P_m \), Eq. (4.11) is dependent on the pump efficiency, \( \eta_p \), (loss in efficiency from the shaft to the power), the motor efficiency, \( \eta_m \), (loss in efficiencies due to the conversion of electric energy to kinetic energy) and the hydraulic power, \( P_h \).

\[
P_m = \frac{P_h/\eta_p}{\eta_m} \tag{4.11}
\]

The hydraulic power is the power needed to move the fluid and overcome pressure differences in the system and was calculated according to Eq. (4.12) (Munson et al., 2012).
\[
P_h = \dot{V}\rho_w g H_p
\]

where, \(\dot{V}\) is the volumetric flow rate, \(\rho_w\) is the density of the fluid (in this case water), \(g\) is the acceleration due to gravity and \(H_p\) is the pump head. The pump head is the pressure loss across two points in a system and was converted from Pascals to metres by Eq. (4.13).

\[
H_p = \frac{P_1 - P_2}{\rho_w g}
\]

Without the availability of pressure measurements an energy balance is typically used as per Eq. (4.14).

\[
\frac{P_1}{\rho_w g} + \frac{v_{f1}^2}{2g} + z_1 = \frac{P_2}{\rho_w g} + \frac{v_{f2}^2}{2g} + z_2 + h_l
\]

\(z_1\) and \(z_2\) are the elevation heads and \(z_1\) is taken as the vertical datum and set to 0. The pipe diameter is constant at the start and end of the points of measurement so the velocity terms cancel and the problem reduces to Eq. (4.15).

\[
H_p = z_2 + h_l
\]

where, \(z_2\) is the static head, (height that the pump needs to overcome), for closed loop systems this is equal to zero, but in this experimental open looped system the highest point in the system was elevated at a height of 1.6 m. \(h_l\) is the head loss due to frictional and local losses throughout the system and was calculated according to Eq. (4.16).

\[
h_l = \sum f \frac{\Delta L}{D_i} \frac{v_f^2}{2g} + \sum \kappa \frac{v_f^2}{2g}
\]

where \(\Delta L\) is the length of pipe, \(v_f\) is the velocity of the fluid, \(D_i\) is the pipe diameter, \(f\) is the friction factor and \(\kappa\) is the local loss coefficient taken from the literature for different fittings and fixtures. The friction factor is dependent on whether the flow is laminar or turbulent and is a function of the Reynolds...
number which is a dimensionless number that relates the inertial forces to the viscous forces Eq. (4.17).

\[ Re = \frac{\rho \nu_l D_i}{\mu} \]  

Eq. (4.17)

where \( \mu \) is dynamic viscosity and is equal to 0.001 N \( s/m^2 \) for water at 20 °C (Munson et al., 2012). The velocity of the fluid, \( \nu_f \), is equal to the volumetric flow rate, \( \dot{V} \), divided by the cross sectional area, \( A_p \), of the pipe.

\[ \nu_f = \frac{\dot{V}}{A_p} \]  

Eq. (4.18)

The Darcy Weisbach friction factor, \( f \), is dependent on whether the flow is laminar (\( Re < 2500 \)) or turbulent (\( Re > 2500 \)). The flow rate dictates whether the flow is laminar or turbulent. For laminar flow a linear relationship between the friction factor and the Reynolds number exists as in Eq. (4.19).

\[ f = \frac{64}{Re} \]  

Eq. (4.19)

Blasius’ explicit equation for the Darcy Weisbach friction factor was applied for turbulent flow regimes Eq. (4.20) (Munson et al., 2012).

\[ f = 0.316 Re^{-0.25} \]  

Eq. (4.20)

The head loss was subsequently calculated for the given system (following Eq. (4.15 to Eq. (4.20)), including both the plastic pipes connecting tank and collector and heat exchanger within the CSC. The head is plotted in Figure 4.19 as a function of the mass flow rate.
From the theoretical measurements, a transition from laminar to turbulent flow was observed at about 0.025 kg/s resulting in an increase in the rate of head loss. DGS (2010) note that pump efficiencies can be as low as 2% in specific systems while Peuser et al. (2010) investigated a pump with an efficiency of 10%. Assuming a pump efficiency of 10% and motor efficiency of 85% the theoretical power curve for this system is presented in Figure 4.10.

In theory, the hydraulic power required to move the water is less than 1 W for a flow rate less than 0.04 kg/s (i.e. typical operating rates). The hydraulic power is the amount of power consumed by a 100% efficient pump. Including the theoretical efficiency of the pump (10%) and the motor (85%) resulted in a dramatic increase in power usage. As the flow rate increases the power requirement increases. Since a greater flow rate would extract more of the available heat, an optimization problem exists here which depends on the specific installed system.
4.3.5.3 Pressure measurements

In the previous section the head loss was calculated theoretically. To validate the mechanical model, pressure recordings were taken for various flow rates and the results are plotted using Eq. (4.13).

Figure 4.21. Head loss as a function of mass flow rate for both theoretical and pressure measurements.

A strong correlation between the theoretical and measured head loss is shown in Figure 4.21. The observed relationship is not linear with the rate of change in head loss increasing with increasing mass flow rate.

4.3.5.4 Power measurements

To measure the actual power consumed by the pump a power meter was used. These results are compared with the theoretical measurements in Figure 4.22.

Figure 4.22. Power consumption of pump
The results show that the installed pump was operating at an even lower efficiency than 10%, meaning that the pump in the experimental set-up was running at an efficiency of approximately 4.5% for higher flow rates and less than 1% for low flow rates. These extremely low efficiencies could be attributed to the age and unsuitability of the pump installed in the experimental set-up.

The poor efficiency of pumps used in solar thermal systems (= 5-10%) is a fact of the modern day solar thermal installations (DGS, 2010; Peuser et al., 2010). While some manufacturers have worked on improving the efficiency of their pumps for solar thermal systems (characterised by relatively high head and low flow rate) more work is needed to improve the efficiency further. As an example, for the given system, a pump with an efficiency of 10% running for 8 hours at a flow rate of 0.02 kg/s consumes 0.04 kWh of electricity while a pump with an efficiency of 1% (similar to the particularly inefficient installed pump) uses 0.4 kWh per day. The electrical energy consumed by the pump needs to be offset against the renewable thermal energy extracted from the CSCs; this highlights the pump power as an important factor in solar thermal systems. In the following energy assessment of a CSC, both the actual pump as well as the theoretical energy used by standard pump efficiencies is investigated.

4.3.6 Energy

The rate of energy gain from the CSCs is compared with the available solar radiation on a 1 m² vertically installed surface for the 25th of March in Figure 4.23. The energy gained from the CSCs divided by the total available energy is the daily efficiency. The daily efficiency is equal to 48% for this particular day.

Comparisons between the energy from the system, $Q_{u,sys}$, and from the collectors only, $Q_{u,dis}$, are shown in Figure 4.24. The energy calculated from the system was slightly lower than the energy from the collectors on the sunny days as heat is lost from the pipes. Over the six days the system-based calculations yield an energy output of 5.55 kWh while the collector based calculations yield an energy output of 5.23 kWh. The system calculations gave an energy output of 6% higher than the collectors. Depending on the sunshine intensity during the day the pipes may add to, or reduce, the energy from the collectors. For example on the 25th of March the pipes loose heat when exiting the collector and returning to the tank (as previously discussed in Section 4.3.3) while on the 27th of March some heat is gained by the exposed pipes during the morning when the temperature of the fluid is low.
Figure 4.23. Energy rate from the concrete solar collectors compared with the solar irradiance.

Figure 4.24. Comparison in Energy output calculations between the system and the collector.

The energy output of the system after taking the pumping requirements into account are displayed in Figure 4.25. The energy consumed by the pump was based on the power consumed for a flow rate of 0.02 kg/s. For the actual pump, interpolation was used to estimate a power consumption of 34 W. For the theoretical pump, the power consumption would be 4.4 W. The duration the pump is on for was taken as the time between the occurrence of the minimum and maximum tank temperatures.
The electrical energy used by the pump reduced the energy output from 5.5 kWh to 3.8 kWh when considering the pump energy demand with the installed pump and from 5.5 kWh to 5.2 kWh when considering the pump energy demand with a standard pump over the course of six days. This equates to 3.2 kWh of thermal energy output per kWh of electric energy used by the pump for 1% efficiency pump and 18.3 kWh for the 10% efficiency pump.

4.4 System alterations

In general, the system was set to operate at the same conditions throughout the year but some changes were made throughout the duration of data recording. These changes are analysed in this section by comparing two most similar days.

4.4.1 Manually controlled pump

Figure 4.26 shows how the system would perform if a controller was installed to only operate the pump when there are available energy gains. The pump was manually switched off at 4PM and when the water drained back the valve closed. The heat lost from the tank after this time was no longer influenced by the CSCs and instead of a significant drop in tank temperature overnight (as seen in Figure 4.12) a temperature drop of less than 5 °C was observed. This heat loss is associated with the temperature difference between the tank and the indoor ambient temperature, as well as the amount and quality of tank insulation. The storage tank used in this system was surrounded by a 20 mm thick spray foam insulation with a manufacturer specified thermal conductivity of 0.03 W/mK. The pump was switched
back on the next day once the temperature of the surface was greater than the temperature in the tank. The use of a controller is further explored using simulation methods in Chapter 5.

![Graph](image_url)

Figure 4.26. The performance of the concrete solar collector system if a controller was to be used.

4.4.2 Insulation

Within the literature, CSCs have been tested with and without insulation at the back. For a façade integrated application, the CSCs should be insulated at the back to minimise heat loss from the CSC and also to minimise the influence with the building’s interior. The performance of the experimental set-up before and after being insulated is presented in Figure 4.27.

Both the 29th of September and 9th of October display similar weather conditions, with the 9th of October experiencing less solar radiation throughout the day. Even though 9th of October had less solar radiation it still produced a slightly higher tank temperature. This improved performance is therefore attributed to the insulation adhered to the back of the CSCs. The effect of the back insulation is further highlighted by comparing the average backside surface temperature of the CSC. The CSC with insulation displays both a higher and more stable temperature at the back of the collector throughout the day.
4.4.3 Tank volume

Heating a greater volume of water requires more energy from the CSCs to achieve the same temperature than heating a smaller volume of water. The tank had less water during a period in June to only hold 35 L of water compared with the 65 L used throughout the experiment. While two identical days were difficult to identify, useful comparisons can be made from Figure 4.28.

The total solar radiation for the 24th of June (2.3 kWh/day) was greater than the total solar radiation for the 14th of June (2.1 kWh/day). However, the maximum tank temperature reached on the 14th was greater (35 °C) than the 24th of June (31 °C). This is attributed to the smaller volume of water in the tank. While a greater amount of energy was stored using a larger tank, the actual temperatures attained were further away than the temperatures required for building application purposes. It is therefore important to size the tank such that it can achieve temperatures close to application temperatures and loads (e.g. typically 52 °C for showers and 35 °C for hand washing).
4.4.4 Flow rate

The highest achievable temperatures were recorded with smaller volumes of storage water. Running the system for two perfectly clear days in summer with record high ambient temperatures for that year show what maximum temperatures can be achieved by the experimental set-up. These results are displayed for two different flow rates in Figure 4.29. The two days show maximum tank temperatures of 45 °C and 40 °C respectively. These results highlight the fact that even with optimum conditions in Ireland, CSCs could not reach the required 52 °C for shower heating purposes and should always be constructed in conjunction with an auxiliary heating system. This is nothing new to solar thermal installations in Ireland (and any other climates that experience cloudy days) which should all be installed with an auxiliary heat supply.

An additional noteworthy observation is the higher outlet temperature on the 18th of June when the flow rate was reduced. The outlet temperature reached almost 50 °C, but given the lower flow rate the tank temperature could not reach this. On the 17th of June the tank temperature was almost the same as the outlet temperature because of the greater flow rate and small volume of storage water.

The flow rate is also compared for two identical days with the reference 65 L of storage water in Figure 4.30. The results again show that the system operating with a higher flow rate achieved a higher storage tank temperature.
Figure 4.29. Comparing the performance of two clear summer days with different flow rates.

Figure 4.30. Comparing the performance of the concrete solar collector system for two similar days with two different operating flow rates.
And again, it shows that the system operating with a lower flow rate achieved a higher outlet temperature. Given the greater energy output from a system running with a greater flow rate an optimisation problem exists for individual installations since increasing the flow rate also increases the hydraulic resistance and hence pumping power requirements. This optimisation problem is explored further by simulation in Chapter 6.

4.5 Conclusions for Chapter 4

Approximately one quarter of the annual energy demand of a single occupant dwelling can be provided by CSCs installed on a south facing façade in Dublin (Ireland) and useful thermal energy can be harvested by vertical façade collectors on clear days in winter months. Peak daily energy outputs are observed in spring and autumn but on average summer months exhibit the greatest daily energy output due to the higher ambient temperature. A daily solar fraction greater than 50% was not observed for any single day of any of the four seasons in Dublin. This is due to the unglazed nature of the CSC and its subsequent inability to reach application temperatures greater than 50 °C. A CSC must therefore be used with an auxiliary heating source. The experimental study was limited to a specific CSC and system in a specific climate. To address these experimental limitations, numerical models are used in the following chapters to assess the thermal contours within the concrete matrix and to investigate different CSCs, different systems and different climates.
Chapter 5

Simulating the Performance of a Concrete Solar Collector
5 Simulating the Performance of a Concrete Solar Collector

A detailed 3D finite element model of the Concrete Solar Collector (CSC), developed in COMSOL Multiphysics, is presented in this chapter. Specifically, this chapter describes the development, verification and validation of the CSC model in Sections 5.1 and 5.2. The temperature distribution throughout the CSCs is presented in Section 5.3 using detailed thermal imaging produced from the 3D CFD model. Performance results are then presented for the CSC as part of a system with real hot water loads and other components which are not included in the experimental set-up (Section 5.4). To date, no detailed 3D models of a concrete solar collector exist. The geometry of the CSC along with the non-negligible thermal mass highlights a requirement for such a model.

5.1 3D model development

The 3D geometry of the CSC model is displayed in Figure 5.1. The three smaller CSCs were first theoretically pushed together (area remained the same) into one long CSC to reduce computational effort without significantly influencing the results. This assumption is allowed for because the edges are all insulated in the experimental setup. Dimensions of the CSCs are also displayed in this figure.

![Figure 5.1. CAD drawing of a concrete solar collector, showing the embedded pipe layout applied in the 3D model.](image)

5.1.1 Model assumptions

This 3D numerical model minimizes the simplifications and assumptions typical to CSC models from previous studies. The remaining assumptions and their associated effects are summarised in Table 5.1.
Table 5.1. Model assumptions, comparison with experiment and associated benefits of the assumption.

<table>
<thead>
<tr>
<th>Model assumption</th>
<th>Comparison with experimental study</th>
<th>Benefit of assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect insulation at the edges</td>
<td>100 mm of high performance insulation is used in the experiment resulting in small heat losses around the edges.</td>
<td>Reduces computational effort.</td>
</tr>
<tr>
<td>A 1m² (1.8 × 0.6 m) collector is the same as three 0.33m² collectors connected in series.</td>
<td>Heat transfer between connecting panels is made negligible in the experiment by insulating the connecting pipes.</td>
<td>Reduces simulation time and geometry complexity.</td>
</tr>
<tr>
<td>Perfect contact between pipe and concrete and between concrete and insulation</td>
<td>Good thermal contact between the pipe and concrete is observed in a cut through a sample CSC (Figure 5.2).</td>
<td>A typical assumption in heat transfer problems that reduces simulation time and complexity.</td>
</tr>
<tr>
<td>2-hour average smoothing applied to the mass flow rate.</td>
<td>Irregular peaks and troughs in the flow rate measurements are smoothed out using 2-hour average smoothing, displayed in Figure 5.3.</td>
<td>Improves model convergence and hence simulation time without significantly influencing the results</td>
</tr>
</tbody>
</table>

Figure 5.2. A section cut through a prototype concrete collector, showing good contact between the pipe and concrete.

In the experimental set-up the flow rate was set to approximately 0.02 kg/s but natural fluctuations above and below this value were recorded. For validation purposes the flow rate was implemented in
the model as a function of time by applying a 2-hour average smoothing to the data. This 2-hour average smoothing is displayed in Figure 5.3 over the course of a 10-day period which includes flow rates ranging from 0.025 kg/s to 0.005 kg/s.

![Figure 5.3. Measured mass flow rate as a function of time with 2 hour smoothing.](image)

5.1.2 Input parameters

The performance of a CSC is subject to a wide range of input parameters. These include fixed inputs such as the geometric dimensions and material properties that define the CSC, as well as time dependent inputs such as the ambient temperature and the solar irradiance. The input parameters included those that were measured on site, measured at a local weather station, calculated from an empirical model or taken from the literature. A summary of all the inputs, their values, their source and their associated inaccuracies is provided in Table 5.2.

5.1.3 Model description

A concrete solar collector may be described as a time dependent, three-dimensional heat transfer problem coupled with internal fluid flow. A general form of the equations governing the heat transfer process in the solid sections of the collector is described by Fourier’s conduction equation, Eq. (5.1) (Incropera, 2013).

\[
\rho c_p \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

Eq. (5.1)
Table 5.2. Summary of all model inputs.

<table>
<thead>
<tr>
<th>Measured material properties and geometric dimensions of the concrete solar collector</th>
<th>Appendix B</th>
<th>Meanings and Arrangement of Data</th>
<th>Accuracy/Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Instrumentation</td>
<td>Model/type</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>Concrete thermal conductivity, $k_c$ (W/mK)</td>
<td>Hot plate test</td>
<td></td>
<td>± 0.18 W/mK</td>
</tr>
<tr>
<td>Concrete density, $\rho_c$ (kg/m$^3$)</td>
<td>Weight in water &amp; air</td>
<td></td>
<td>± 10 kg/m$^3$</td>
</tr>
<tr>
<td>Solar absorptance, $\alpha$</td>
<td>Integrated sphere set-up</td>
<td></td>
<td>± 0.02</td>
</tr>
<tr>
<td>Pipe diameter, $D_i$ (m)</td>
<td>Measuring tape</td>
<td></td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Pipe plane depth, $D_{emb}$ (m)</td>
<td>Measuring tape</td>
<td></td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Pipe spacing, $D_s$ (m)</td>
<td>Measuring tape</td>
<td></td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Panel thickness, $\delta$ (m)</td>
<td>Measuring tape</td>
<td></td>
<td>± 1 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured external conditions on site</th>
<th>Instrumentation</th>
<th>Model/type</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance, $I_s$ (W/m$^2$)</td>
<td>Pyranometer</td>
<td>Kipp &amp; Zonen CMP 11</td>
<td>&lt; 5.25%</td>
</tr>
<tr>
<td>Average wind speed, $v_w$ (m/s)</td>
<td>Anemometer</td>
<td>Young 05103</td>
<td>± 0.3 m/s</td>
</tr>
<tr>
<td>Ambient temperature, $T_a$ (°C)</td>
<td>Thermocouple</td>
<td>Type K</td>
<td>± 0.05 K</td>
</tr>
<tr>
<td>Flow rate, $\dot{m}$ (kg/s)</td>
<td>Magnetic induced flow meter</td>
<td>IFM SM8000</td>
<td>± 0.0023 kg/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured external conditions at a local weather station</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud cover, $C_{l,cov}$ (Oktas)</td>
<td>(Met Éireann, 2013) Dublin airport</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculated inputs</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky temperature, $T_{sky}$ (°C)</td>
<td>(Martin &amp; Berdahl, 1984) and (Berdahl &amp; Martin, 1984)</td>
</tr>
<tr>
<td>Forced convective heat transfer coefficient, $h_{conv}$ (W/m$^2$)</td>
<td>(Churchill &amp; Ozoe, 1973)</td>
</tr>
<tr>
<td>Natural convective heat transfer coefficient, $h_{nat}$ (W/m$^2$)</td>
<td>(Churchill &amp; Chu, 1975)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inputs taken from the literature</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete specific heat capacity, $c_c$ (J/kg.K)</td>
<td>(Incropera &amp; DeWitt, 1996)</td>
</tr>
<tr>
<td>Water specific heat capacity, $c_w$ (J/kg.K)</td>
<td>(BS ISO 10456, 2009)</td>
</tr>
<tr>
<td>Water thermal conductivity, $k_w$ (W/m.K)</td>
<td>(BS ISO 10456, 2009)</td>
</tr>
<tr>
<td>Water density, $\rho_w$ (W/m.K)</td>
<td>(BS ISO 10456, 2009)</td>
</tr>
<tr>
<td>Thermal emittance, $\epsilon$</td>
<td>(Incropera &amp; DeWitt, 1996)</td>
</tr>
</tbody>
</table>
where, $\rho_c, c_c$ and $k_c$ are the density, heat capacity and thermal conductivity of the concrete matrix. $T$ is the absolute temperature; $x$, $y$ and $z$ are the spatial independent variables (these are replaced by the $\nabla$ symbol, for the vector partial derivative, in subsequent equations) and $t$ is the independent variable for time. At a point on the exposed surface of the CSC, the external conditions are such that the equation becomes:

$$\rho_c c_c \frac{\partial T}{\partial t} = k_c \nabla^2 T + Q'_{r,sh} + Q'_{c,f} + Q'_{c,n} + Q'_{r,t} \tag{5.2}$$

where $Q'_{r,sh}$ is the shortwave radiation incident on the collector and $Q'_{c,f}, Q'_{c,n}$ and $Q'_{r,t}$ are the heat losses associated with forced convection from wind, natural convection from the surrounding air and diffuse longwave radiation to the sky and the surroundings. The heat transfer is represented by Equation 5.3 for an element contacting the fluid.

$$\rho_p c_p \frac{\partial T}{\partial t} = k_p \nabla^2 T + Q_{fluid} \tag{5.3}$$

where, $\rho_p, c_p$ and $k_p$ are the density, heat capacity and thermal conductivity of the pipe (in this case copper) and $Q_{fluid}$ is the term used to represent the heat extracted by the fluid within the pipe. For energy conservation in the fluid domain the heat transfer equation is described by Eq. (5.4).

$$\rho_w c_w \left( \frac{\partial T}{\partial t} + (u \cdot \nabla)T \right) = -k_w \nabla^2 T + Q_{wall} \tag{5.4}$$

where, $\rho_w, c_w$ and $k_w$ are the density, heat capacity and thermal conductivity of the fluid (in this case water), $u$ is the velocity vector and $Q_{wall}$ is the term used to represent the heat from the pipe wall. Localised turbulence may occur at the pipe bends but the given flow rate results in a low Reynolds number ($< 2500$), representing laminar flow. Additionally, laminar flow was visually observed for flow rates lower than 0.03 kg/s. This laminar fluid motion is described by the Navier Stokes equations. These are the governing equations for the incompressible fluid flow in the model i.e. the conservation of momentum (Eq. (5.5)) (COMSOL, 2013).

$$\rho_w \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \nabla \cdot (\mu (\nabla u + (\nabla u)^T)) + F \tag{5.5}$$

and the conservation of mass (Eq. (5.6))
\[ \frac{\partial \rho_w}{\partial t} + \nabla (\rho_w \mathbf{u}) = 0 \]  
\text{Eq. (5.6)}

where \( \mu_f \) is the dynamic viscosity of the fluid and \( F \) is the body force vector. No slip temperature \( (T_{\text{pipe,wall}} = T_{\text{fluid,wall}}) \) and velocity \( (u_{\text{fluid,wall}} = 0) \) boundary conditions were applied at the interface between the fluid and pipe wall. A uniform temperature boundary condition was prescribed to the inlet, \( T_i \), based on experimentally recorded values. At the outlet of the pipe an open boundary was applied and recorded to calculate the outlet temperature, \( T_o \), from which the useful rate of energy out can be calculated from Eq. (5.7).

\[ \dot{Q}_u = m c_w (T_o - T_i) \]  
\text{Eq. (5.7)}

5.1.4 Surface boundary conditions

The edges of the CSC were assumed to be perfectly insulated meaning there was not heat loss or gain. The front and back surface was subjected to heat losses and the front was also subjected to gains from the external conditions. In a real integrated application, the back would be subjected to interior conditions, but for validation purposes the model was required to match the experimental setup, which was exposed to the elements at the back of the insulation. The appropriate boundary conditions were subsequently used to match the experimental set-up.

5.1.4.1 Shortwave radiation

Radiation from the sun is absorbed by the concrete surface in accordance with Eq. (5.8).

\[ \dot{Q}_{r,\text{sh}} = \alpha A_c I_s \]  
\text{Eq. (5.8)}

where \( \alpha \) is the solar absorptance, \( A_c \) is the surface area of the concrete exposed to the sunlight and \( I_s \) is the measured irradiance (W/m\(^2\)).

5.1.4.2 Longwave radiation

Heat was also lost from the surface of the CSC to the surroundings by longwave thermal emission in accordance with Eq. (5.9).

\[ \dot{Q}_{r,\text{l}} = \varepsilon \sigma A (T_{\text{sky}}^4 - T^4) \]  
\text{Eq. (5.9)}

where \( \varepsilon \) is thermal emissivity and \( \sigma \) is the Stefan Boltzmann constant. For vertical surfaces the surrounding temperature was taken as the average between the effective sky temperature, \( T_{\text{sky}} \), and the
ambient temperature, $T_a$ (D’Antoni & Saro, 2013). Numerous effective sky temperature models exist as documented by Algarni & Nutter (2015), ranging from simple empirical models which are only a function of the ambient temperature (Fuentes, 1987; Swinbank, 1964) to more sophisticated models that are also a function of other parameters such as the dew point temperature and cloud cover (Berdahl & Martin, 1984; Martin & Berdahl, 1984). The simple empirical models are solely based on the ambient temperature and are particularly popular and useful for forecasting or validating a model over a short time period where there is no significant change in cloud cover. The empirical models used in this study for effective sky temperature estimation (Berdahl & Martin, 1984; Martin & Berdahl, 1984) provide accuracy over a range of climates for both cloudy and clear days. The sky temperature was described by these models as per Eq. (5.10) to Eq. (5.12).

$$T_{sky} = \left(\varepsilon_{sky}\right)^{0.25} T_a$$  \hspace{1cm} \text{Eq. (5.10)}$$

where $\varepsilon_{sky}$ is the sky emissivity and was calculated according to Eq. (5.11).

$$\varepsilon_{sky} = \varepsilon_{clear \sky} + \left(1 - \varepsilon_{clear \sky}\right) f_{cloud}$$  \hspace{1cm} \text{Eq. (5.11)}$$

where $\varepsilon_{clear \sky}$ is the clear sky emissivity and $f_{cloud}$ is the cloud sky fraction ranging from 0 for a clear sky to 1 for a completely cloudy sky. In this study, the cloud sky fraction was converted from Oktas (as measured by Met Eireann). For example, a partly cloudy day of 4 out of 8 Oktas represents a cloud sky fraction of 0.5. The clear sky emissivity was calculated according to Eq. (5.12).

$$\varepsilon_{clear \sky} = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right) + 0.73\left(\frac{T_{dp}}{100}\right)^2$$  \hspace{1cm} \text{Eq. (5.12)}$$

where $T_{dp}$ is the dew point temperature (as measured by Met Eireann).

5.1.4.3 Convective losses

For solar collectors without glazing, as with these CSCs, significant heat losses are associated with convection directly from the absorber. Heat is lost from the surface by forced convection, $Q_{c.f}$, resulting from the wind, as well as natural convection, $Q_{c.n}$, from natural buoyancy in the air adjacent to the collector. The same convective boundary conditions were applied to the front surface of the concrete and the back of the insulation in the CSC model. The forced convection is described in Eq. (5.13).

$$Q_{c.f} = h_{wind} A_c (T_a - T_{surf})$$  \hspace{1cm} \text{Eq. (5.13)}$$
where $T_{surf}$ is the temperature of the surface and $h_{wind}$ is the averaged heat transfer coefficient due to the wind. It is based on the empirical correlation of Churchill & Ozoe (1973) for external convection of a flat plate, given by Eq. (5.14).

$$h_{wind} = \begin{cases} 2 \frac{k_a}{L} \frac{0.3387 P_r^{1/3} Re_L}{(1 + (0.0468/P_r)^{2/3})^{1/4}} & Re_L \leq 500,000 \\ 2 \frac{k_a}{L} P_r^{1/4} \left(0.037 Re_L^{5/4} - 871\right) & Re_L \geq 500,000 \end{cases}$$

Eq. (5.14)

where $L$ is the length of the CSC, $k_a$ is the thermal conductivity of the air. $Pr$ and $Re_L$ are the Prandtl number and Reynolds number respectively. The Reynolds number is given by Eq. (5.15).

$$Re_L = \frac{\rho_a v_w L}{\mu}$$

Eq. (5.15)

where $\rho_a$ is the density of the air and $v_w$ is the velocity of the air (i.e. the wind speed). The Prandtl number is given by Eq. (5.16).

$$Pr = \frac{\mu a c_a}{k_a}$$

Eq. (5.16)

where $\mu_a$ is the dynamic viscosity of air and $c_a$ is the specific heat capacity of air. The natural convective heat loss from the vertical surface was calculated according to Eq. (5.17).

$$Q_{c,n} = h_{nat} A_c (T_a - T_{surf})$$

Eq. (5.17)

where $h_{nat}$ is natural convective heat transfer coefficient evaluated based on the Churchill & Chu (1975) correlation for natural convection of vertical plates. It is given by Eq. (5.18).
which is determined based on the Rayleigh number, which is equal to the product of the Prandtl and the Grashof number. Grashof’s number is calculated according to Eq. (5.19).

\[
Gr_L = \frac{g\beta\Delta TL^3}{\left(\mu_a\rho_a\right)^2}
\]  

Eq. (5.19)  

where \(\Delta T\) is the temperature difference between the air and the surface, \(\beta\) is the thermal expansion of the air and \(H\) is the height of the collectors.

5.1.5 Finite element mesh development and model verification

5.1.5.1 Finite element solver

Numerical methods were used to solve the described equations. These were solved in COMSOL Multiphysics Finite Element Software which works by dividing the geometry into a number of discrete elements (finite elements). A set of equations are associated with each element which are solved collectively or in groups. For this specific problem, a segregated solution approach was used where the dependent variables were split into two groups (systems of equations), one for temperature \((T)\) and the other group for velocity \((u)\) and pressure \((P)\). Both groups were solved using the direct PARDISO solver and the results were passed between each segregated group until both systems converged (COMSOL, 2013). A relative tolerance was used as the convergence criteria. A relative error tolerance of 0.001 (Leone & Beccali, 2016) was pre-defined in the model so that the model was only deemed to have converged for each time step when the exact solution was within this pre-defined tolerance of the numerical solution.
Neglecting the importance of the initial conditions can result in lengthy convergence times. To avoid unnecessarily long convergence times the problem was split into two steps. First a steady state simulation was computed, using the external boundary conditions associated with the time \( t = 0 \). The solution was stored and subsequently used as the initial conditions for the time dependent simulation.

### 5.1.5.2 Geometry verification

One of the assumptions made in the modelling of the CSCs was that the three collectors, which were connected in series and insulated at the edges, can be represented by one long collector. To verify this assumption both geometries are modelled over a sample day (25th of March 2018) and the results are compared in Figure 5.4. The results are presented in terms of the outlet water temperature, \( T_o \), and display almost identical profiles. This result verifies the geometric assumption made in the model which increases the simulation time by reducing the number of elements to be solved for.

![Figure 5.4](image.png)

**Figure 5.4.** Verification of assumption that three collectors insulated and connected in series can be represented by one long collector of equal concrete area.

### 5.1.5.3 Mesh verification

The numerical solution is only an approximation of the real analytical solution, which, like most complex 3D geometry problems, is often too difficult to obtain. Increasing the number of finite elements and reducing their size generally results in an approximation closer to the actual solution. However, computational effort is also increased. Computational effort was reduced by increasing the finite element mesh resolution only at sections in the domain where a high resolution is important, i.e. where high temperature gradients exist.
The mesh was developed to minimise computational effort without significantly affecting the accuracy. The CSC geometry was divided into three domains for meshing purposes, namely, 1) the pipe and the fluid, 2) the surrounding concrete and, 3) the back insulation. The serpentine style pipe and fluid, illustrated in Figure 5.1, was first meshed using long prismatic elements to provide a denser mesh perpendicular to the fluid flow. The surrounding concrete was meshed using tetrahedral elements around the pipe bends and prismatic elements around the pipe lengths. Prismatic elements were used on the back insulation of the CSC. The fineness of the mesh was increased around the pipe. The development of the mesh is displayed in Figure 5.5.

Figure 5.5. Finite element mesh used in this study (Mesh 3) along with zoomed in images of three other trial meshes.

A coarse mesh was first developed (Mesh 1) to obtain preliminary results. Mesh 2 was developed after, which increases the mesh density of the fluid, as can be seen by zoom frame (ii) of Figure 5.5. The fluid mesh was further improved at the boundary between the pipe wall and the surrounding concrete in Mesh 3. In Mesh 4 the number of mesh elements were increased again by significantly increasing the number of fluid elements as well as increasing the number of elements following the straight sections of the pipe (Zoom Frame (ii) from Figure 5.5). Simulations of each mesh were computed, and the results were compared for verification. This verification process used to select the most suitable mesh is displayed in Figure 5.6.
Figure 5.6. Finite element mesh comparison for two different flow rates using the percentage mean absolute error of the outlet temperature as the comparison metric. Mesh 3 is subsequently used in this study.

The results for a sample day are displayed for all four meshes. It is evident that, despite the significant increase in simulation completion time, there are no significant improvements to be achieved from increasing the mesh density to that of Mesh 4. Subsequently Mesh 3 was selected as the most appropriate FE mesh and was used in this thesis for all subsequent simulations of the CSC.

5.1.6 System model

The described FE model of the concrete solar collector was also used as a part of a solar thermal system. In this section four systems are explored for investigation purposes, as presented in Figure 5.7.
Figure 5.7. Concrete solar collector systems considered in this study. System (i) and (ii) are representative of the experiment while systems (iii) and (iv) include additional components in the system; namely a controller and a hot water load.

System (i) is concerned only with the concrete solar collector where the inlet temperature was updated at each time step based on experimentally recorded (or known) data. System (ii) represents the experimental set-up and the inlet condition was only set in the model for the initial time step, after which it was set equal to the tank temperature of the previous time step.

The storage tank holds 65 L of water and was insulated with 30 mm of insulation foam. While low flow systems usually induce thermal stratification in the storage tank, the geometry of the storage tank used and the mixing induced by the direct nature of the system allows for the assumption of a fully mixed storage tank. An average difference between the three thermocouples located in the tank (Chapter 4) over a six-day period of 1 °C allows for this assumption. While a fully mixed storage tank is convenient for modelling purposes it has already been noted in Chapter 4 that this reduces the performance of the overall system.

To allow for the assumption that the plastic pipes (connecting the CSCs (with embedded copper pipes) and the tank) have a minimal influence on the performance of System (ii), the pipes in the experiment were insulated with 30 mm insulation and wrapped in a reflective foil.
5.1.6.1 System (i) - collector only

For System (i) the inlet temperature was updated at each time step based on experimentally measured data. A real example of such a system is one where water enters the collectors from the mains water source or an elevated reservoir on site and is used directly. The water is not fed back to a storage tank so the inlet temperature is independent of the outlet temperature from the previous times. Such a system uses hydrostatic pressure head and would not require a pump. The rate of useful energy output was calculated according to Eq. (4.1). In this study, System (i) serves as a tool for validating the CSC as an individual component. It is also beneficial for performance characterisation as it does not include any other components of a system and is used in a later chapter (Chapter 6) because of this advantage.

5.1.6.2 System (ii) - collector and tank

With System (ii) a storage tank was added to the model. For this model the inlet temperature is no longer a measured input; instead it is updated based on the storage tank temperature which was modelled using a 1D approximation based on an energy balance, described in Eq. (5.20) using the simple Euler integration format (Duffie & Beckman, 2013).

\[ T_{tank} = T_{tank}^{t-1} + \frac{\Delta t_{step}}{m_{tank}c_f} [Q_u - \dot{Q}_{loss}] \]  

Eq. (5.20)

where, \( \dot{Q}_{loss} \) is the heat loss which is calculated according to Eq. (5.21).

\[ \dot{Q}_{loss} = U_{tank}A_{tank}(T_{tank} - T_{a,in}) \]  

Eq. (5.21)

and, \( T_{tank} \) is the tank temperature, \( T_{a,in} \) is the indoor ambient temperature. \( m_{tank} \), \( U_{tank} \) and \( A_{tank} \) are the mass, thermal transmittance and exposed surface area of the tank. \( T_{tank}^{t-1} \) is the tank temperature from the previous time-step. The duration of the time-step, \( \Delta t_{step} \), is set to 5 minutes. Since the plastic pipes connecting the tank to the collector were neglected, the inlet temperature was let equal to the tank temperature from the previous time step (\( T_i = T_{tank}^{t-1} \)). Both simulated systems (i) and (ii) were validated against experimentally measured results and are compared in Section 5.2.

5.1.6.3 System (iii) - collector, tank and controller

For System (iii) a controller was included to pump the water into the tank only when the outlet temperature of the collector was greater than the inlet/tank temperature. To model this, only positive useful energy values should be used, and \( \dot{Q}_u \) in Eq. (5.20) was subsequently replaced with \( \dot{Q}_u^+ \). A controller is used in any real solar thermal system application where a feedback system is used. Manual operation of the pump is not commonplace for real installations.
5.1.6.4 System (iv) - collector, tank, controller and hot water load

For System (iv) Eq. (5.20) was updated to include a hot water load, as per Eq. (5.22).

\[ T_{tank} = T_{tank}^{t-1} + \frac{\Delta t_{step}}{m_{tank}c_f} \left[ Q_u^+ - Q_{loss} - \dot{Q}_{s,load} \right] \]  
Eq. (5.22)

where the portion of the hot water load supplied by solar energy, \( \dot{Q}_{s,load} \), is given by Eq. (5.23).

\[ \dot{Q}_{s,load} = M_{load}c_f(T_{tank} - T_{mains}) \]  
Eq. (5.23)

where \( T_{mains} \) is the mains water temperature and was equal to 11 °C for the month of March (approximated from Gill et al. (2016)). \( M_{load} \) is the mass flow rate of hot water in kg/s (which also varies depending on the application draw-off). Considering the small size of the installed CSC system, the EU reference ‘tapping cycle number 1’ was employed in the model which features 11 draw-offs, including a shower each evening. It is outlined in the European Union mandate for the elaboration and adoption of measurement standards for household appliances (EU M324, 2002). Average flow rates were taken from Jordan & Vajen (2001) for the relevant application. For all draw offs that have a duration of less than 5 minutes the flow rates were reduced so that the same amount of water was consumed within the 5-minute time step which was used in this model. \( T_{app} \) is the application temperature (which varies depending on the application of the draw-off). When the temperature of the storage tank was lower than the application temperature, an auxiliary heater was used. The energy use of the auxiliary heater was calculated using Eq. (5.24).

\[ \dot{Q}_{aux} = M_{load}c_f(T_{app} - T_{tank}) \]  
Eq. (5.24)

5.2 3D Model validation

It is well documented that an explicit standard validation method for solar thermal system models does not exist (Rey & Zmeureanu, 2016), instead validation methods used in similar studies should be employed. In this study the variation between the experimental and simulated temperatures were evaluated using the Percentage Mean Absolute Error (PMAE) following Ayompe et al. (2011). For validation purposes the PMAE is described by Eq. (5.25).

\[ PMAE = \frac{100}{n} \sum_{i=1}^{n} \frac{|Sim_i - Exp_i|}{Exp_i} \]  
Eq. (5.25)
Sim\textsubscript{i} and Exp\textsubscript{i} are the \( i^{th} \) simulated and experimental values and \( n \) is the number of values.

5.2.1 Collector

The collector model was first validated independent of the system by using the inlet temperature as an input (System (i) Figure 5.7). The validation results of the outlet temperature are displayed in Figure 5.8.

A strong validation between simulation and experimental outlet temperature is observed and a PMAE of 1.7\% is calculated for the run of 6 days. A notable error in the results is the underestimation of the experimental outlet temperature at peak irradiance. This may be attributed to errors in the pyranometer reaching their maximum at these higher irradiance values (i.e. 5.3\%).

5.2.2 System

The entire system model was also simulated and validated. Since more assumptions were made with this model (System (ii) Figure 5.7) the errors between simulation and experiment were greater as is displayed in Figure 5.9.
The PMAE for the outlet temperature of the system is 5.5%. Over the course of 6 days the error between the total energy output, $Q_{out}$, is less than 4.1% with the simulated results slightly over estimating the energy output on cloudy days and slightly underestimating the energy output on clear days. A visual representation of this is shown in Figure 5.10.

Figure 5.9. Validation of a concrete solar collector connected with a storage tank (i.e. System ii).

Figure 5.10. The rate of energy output for simulation and experiment.
In addition to the outlet fluid temperature and energy output, three other fluid temperatures and six surface temperatures were measured and validated. The validation results for both System (i) and System (ii) are displayed in Table 5.3.

Table 5.3. Validation of each thermocouple (location given in Figure 3.2) using the percentage mean absolute error (PMAE).

<table>
<thead>
<tr>
<th>Thermocouple (Error! Reference source not found.)</th>
<th>System (i)</th>
<th>System (ii)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector1_inlet (Tf2)</td>
<td>Na</td>
<td>5.6%</td>
</tr>
<tr>
<td>Collector2_inlet (Tf3)</td>
<td>0.8%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Collector3_inlet (Tf4)</td>
<td>1.1%</td>
<td>5.7%</td>
</tr>
<tr>
<td>Collector3_outlet (Tf5)</td>
<td>1.7%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Collector1_FrontCentre (Ts1)</td>
<td>2.9%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Collector2_FrontCentre (Ts2)</td>
<td>2.5%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Collector3_FrontCentre (Ts3)</td>
<td>2.8%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Collector1_BackCentre (Ts4)</td>
<td>2.5%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Collector2_BackCentre (Ts5)</td>
<td>2.1%</td>
<td>5.7%</td>
</tr>
<tr>
<td>Collector3_BackCentre (Ts6)</td>
<td>2.1%</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

The results show a good match between the simulation and experimental results with no single measurement having an error of more than 6.4%. The largest errors were recorded on the front surface which may be attributed to the rough surface finish, which was assumed to be smooth in the model.

5.3 Computational fluid dynamics results

The temperature distribution throughout the CSC domain and the velocity field for the moving fluid are presented in this section using the results of the simulation. The resulting CFD images of the CSC provide high quality visual results that could only be achieved experimentally with hundreds to thousands of thermocouples.

5.3.1 Diurnal temperature variation

The temperature distribution changes throughout the day. The diurnal temperature variation of specific points in the CSC is presented for the experimental set-up in Figure 5.11.
Figure 5.11. Diurnal variation in outlet temperature and associated surface temperature for 1:00 AM, 11:00 AM and 4:00 PM.

During the heat-up phase (CFD figure associated to 11:00 AM), the front surface of the CSC was at the highest temperate. At this time of the day, the highest temperatures on the front surface were located in areas with no pipes embedded directly beneath. This is because the heat is not being as efficiently extracted in these areas. The fluid entering the collector was heated up by the surrounding concrete as it passed through the pipe channel. The heat which was not extracted by the collectors was either temporarily stored in the concrete or lost to the environment.

As explained in Chapter 4, the CSCs were used to cool down the water in the tank overnight. This is evident from the CFD figures at 1:00 AM and 9:00 PM with the fluid entered the CSCs at a higher temperature than when it exited the embedded pipe. Additionally, it can be seen from the image at 9:00 PM in Figure 5.11 that the back of the concrete was at a greater temperature than the front of the concrete, highlighting the effect of the thermal mass. To better examine the temperature at different depths in the CSC a number of section cuts through the CSC were produced during both heat up (11AM) and cool down (9 PM) phases of the CSC’s daily operation. An example of two selected planes during the heat up phase is displayed in Figure 5.12.
The slices are displayed for both the $xy$ and $yz$ planes. The $xy$ plane is located at the centre line of the pipes i.e. the embedment depth. The $yz$ plane is located halfway through the CSC. The temperature distribution of the slices are individually assessed in detail in the following sections.

5.3.2 Heat up

The temperature distribution through the CSC is best understood by presenting section cuts through the FE model. Figure 5.13 presents a selection of section cuts through the CSC at 11:00 AM, a time when the solar radiation was heating the surface of the CSC.
The location of each section cut is visually displayed by the 3D image as well as also being explicitly stated in the text beside the relevant section cut. It is evident from both the xy and yz sections that, at this time in the day, the front surface of the CSC reached the highest temperature, with the average temperature reducing deeper into the CSC. The variation in the temperature of the section cuts closest to the pipe was greatest, with the variation becoming less apparent further away from the pipe. The back of the insulation was at the lowest temperature since it is well protected from any solar gains from the insulation itself. Furthermore, it is evident from most of the slices near the pipes that the temperature increased near the outlet, highlighting an increase in the fluid temperature as it moved through the concrete.

After approximately 4:00 PM the heat losses became greater than the heat gains and the concrete began to cool down. Figure 5.14 presents a selection of section cuts through the CSC at 9:00 PM, during this CSC cool-down phase in the day.
5.3.3 Cool down

During the cool down of the CSC the back of the concrete, just in front of the back insulation, was at the highest temperature with the temperature of the concrete reducing the closer it is to the exposed front surface. The front surface of the CSC was cooling down the fluid entering the CSC from the tank which was at a higher temperature than the front surface. This is opposite to what is happening in Figure 5.13. The circulating fluid and storage capacity of the concrete results in the concrete maintaining a higher temperature than the back insulation which is substantially colder.

5.3.4 Velocity distribution

The velocity of the fluid in the pipes was also simulated by the CFD model and is displayed in Figure 5.15.
The CFD image of the fluid flow shows a greater velocity at the centre of the pipe compared with the boundary. The results also show that there was some turbulent behaviour occurring at the pipe bends, the effect of which is minor given the ratio between the length of pipe bends vs the length of straight pipes. The entrance region was assumed to be constant and the fluid develops into a laminar flow approximately 40 mm after entering the pipe. While this was not the reality (as the system is continuously circulating), the entrance makes up for less than 1% of the overall pipe length and can be neglected as having any significant influence on the simulated performance. Significantly increasing the flow rate would result in turbulent flow in the pipe which would result in a non-uniform fluid velocity distribution in all dimensions and therefore requires a denser fluid meshing. Experimental measurements found that turbulent/transitional flow only became visually noticeable when the flow rate was increased by more than 0.03 kg/s, so laminar flow was only considered in this 3D model.

5.4 Simulation results

The experimental study assesses the real-life performance of a CSC set-up in Dublin. It provides insight into how a CSC system may perform in a real installation. Additionally, it provides real life data against which any model can be validated. However, the experimental investigation was limited to a specific CSC set-up. The 3D CSC model, described in Section 5.1 and validated in Section 5.2, is used in this section to compare the performance of different CSC systems.

Figure 5.15. Velocity profile at the centre of the embedded pipe plane as well as a streamline image of the fluid flow at one of the U-bends.
5.4.1 Controller and heating load

In a real application, the thermal energy stored in a tank would not be discharged overnight through continuous running of the system. This was carried out during experimental investigation to ensure the tank temperature was lowered to approximately mains water temperature so discrete day gains could be analysed. In a real application, a controller would be included to turn the circulation pump off when the system is not collecting any useful heat and a hot water load would be represented with rapid draw offs throughout the day with various flow rates (Figure 5.16) and application temperatures (Figure 5.17). The application temperatures and draw off rates are associated to different end uses which include hand washing, washing machine cycles and showering.

![Figure 5.16. Tapping cycle and draw off rates for a single occupant throughout the day (EU M324, 2002).](image1)

![Figure 5.17. Associated application temperatures for the tapping cycle of Figure 5.16 (EU M324, 2002).](image2)

Modelling results shown here include both a controller and realistic hot water load. The weather data for the run of 6 spring days shown in Chapter 4 plus an additional 4 days is used for the analysis of
Systems (iii) and (iv); the results are displayed in Figure 5.18. The results are extended from the initial 6 days to 10 days to include the performance of the CSC after a run of cloudy days.

![Figure 5.18. Comparison of the storage tank temperature of a system with a controller (iii) and with both a controller and a hot water load (iv).](image)

The differential controller, typical to most solar thermal systems, is programmed in the model so that the pump only switches on when the temperature of the fluid at the outlet of the CSCs is greater than the temperature of the fluid in the tank. For System (iii) operating over the sample 10 days, it is observed that the pump is not in operation for half of the days, where the sunshine is insufficient and no useful energy can be added to the tank. The loss in the tank temperature here was due only to heat lost to the ambient indoor environment of the tank and the rate of temperature reduction is dependent on the tank’s insulation.

A better representation of the energy output of a CSC is provided by System (iv), the tank temperature profile for System (iv) results from a hot water tapping cycle for a single occupant apartment. The applied tapping cycle (described in Section 5.1.6.4) equated to approximately 2.1 kWh/day. The solar irradiance is the clear driving force for the performance of the CSC, with the outlet temperature and subsequently the tank temperature achieving the highest temperatures on the clear sunny days. On the cloudy days, useful energy was only attainable if the outlet temperature was greater than the tank temperature. The tank temperature was dictated by the energy gained from the collectors and the energy used by the occupants from the previous day. On the 28th of March the tank temperature was higher than the outlet temperature of the tank due to the remaining energy extracted from the CSCs from the
previously clear day (27th of March) while on the following day (29th of March) even though the solar radiation was less, there was a small amount of useful energy extracted.

When the maximum thermal energy was extracted from the concrete, and the pump was switched off in late afternoon, the temperature of the fluid did not instantaneously drop to the ambient temperature. Instead a slow cool down of the collector was observed due to the high thermal inertia of the collector. This is shown by the outlet temperature in Figure 5.18 on the clear days.

On the 25th of March the tank reached a maximum temperature of approximately 30°C (15°C higher than the maximum ambient temperature for that day). This day also represented a Solar Fraction (SF) of 37.8% and a daily efficiency, $\eta_d$, of 30%. Discrete changes to individual parameters are investigated in the following subsections with reference to the SF and $\eta_d$ on this day.

### 5.4.2 Interior boundary condition

First a change was made to the back-boundary condition of the CSC to represent the interior of a real dwelling. Assuming the insulation formed the inner wall of a building the convective boundary condition for the back wall was changed from a combination of forced convection due to the wind and natural convection from the outside air to simply just natural convection to the interior as displayed in Eq. (5.26).

$$Q_{in} = h_n A (T_{a, in} - T_{w, in}) \quad \text{Eq. (5.26)}$$

$Q_{in}$ is the heat flux between the inner insulation and the interior of the building. It was assumed that the temperature of the air inside is perfectly controlled and the effect of the CSC on the interior environment is assessed here with reference to the average temperature of the indoor wall $T_{w, in}$.

The CSC was simulated for both the experimental boundary condition (back insulation exposed to external wind and air temperature) and the new interior boundary condition (back insulation exposed to indoor ambient air temperature). The results of both are presented in Figure 5.19 showing that the interior boundary condition had negligible effect on the average tank temperature and hence performance of the CSC. This negligible influence may be attributed to the high-quality insulation used (extruded polystyrene foam, thermal conductivity $\approx 0.03$ W/mK). While the fluid temperatures in the system did not change, the temperatures at the back of the insulation are significantly different. For the indoor boundary case the wall temperature reached a maximum of 2.5°C below the interior air temperature during the morning and a maximum of 2.2°C above the interior air temperature in the evening.
Figure 5.19. The performance of a concrete solar collector exposed to indoor conditions compared with one exposed to external conditions (experimental case).

Simulating an identical system, with no pipes or moving fluid resulted in similar maximum temperature of 2.5°C below the interior air temperature but resulted in a higher temperature difference in the evening (from 2.2 to 3.3°C). This preliminary result shows that CSCs could help cool a building down in the summer months while also extracting useful heat. Removing the insulation at the back altogether and simulating a CSC so that the natural convective losses are due to the outside ambient temperature results in a 1% drop in SF and daily efficiency. The subsequent results and analysis in this section are presented with respect to the indoor boundary condition at the back of the insulation layer, similar to that of a real building integrated system.
5.4.3 Collector area and pipe length

Changing the geometry from three serpentine channels to one single serpentine channel, while maintaining the same pipe length, resulted in a negligible change in performance. Increasing the collector area from 1m² to 2m², while keeping the same length of pipe, resulted in an increase in the SF from 37.8% to 44.4%. Doubling the pipe length for this increased area resulted in only a small additional increase in the tank temperature, as shown in Figure 5.20. This highlights an upper limit on the maximum temperature of approximately 35°C (20°C above ambient outside air temperature) for this given day.

![Concrete solar collector performance with different size and pipe spacing.](image)

Figure 5.20. Concrete solar collector performance with different size and pipe spacing.
5.4.4 Surface absorptance

The results in this study are, so far, presented for a black painted CSC (\( \alpha = 0.94 \)). This dark surface finish, which increases the solar absorptance, could also be achieved by incorporating a pigment in the concrete mixture, a common technique used in precast cladding development. The tank temperature for both a black pigmented concrete (\( \alpha = 0.89 \)) as well as a plain concrete (\( \alpha = 0.7 \)) are plotted in Figure 5.21.

![Concrete solar collector performance with different surface finishes.](image)

The results show a small decrease in the performance of the system when using black pigment in place of black paint (SF reduces from 37.8% to 36.1%). A greater reduction in the performance is observed for a plain grey concrete (SF = 29.3%). While both the plain and black pigmented CSCs were
outperformed by the black painted CSC, they provide a better aesthetic and less maintenance, which is important for building integrated solar thermal solutions.

5.4.5 Flow rate

Reducing the flow rate from the set 0.02 kg/s to 0.005 kg/s resulted in a reduction in performance of the CSC with SF dropping from 37.8% to 34.4% and the $\eta_d$ from 30% to 27.5%. Increasing the flow rate by more than the 0.02 kg/s displayed negligible improvement in the performance. A flow rate of 0.02 kg/s appears to be able to extract the maximum possible thermal energy from this collector for this day. Optimisation of the flow rate, which depends on the available solar energy and pump efficiency, is further assessed in Section 6.4.10. The outlet temperatures, in addition to the tank temperatures, are illustrated in Figure 5.22. While the outlet temperature was higher for the low flow rate of 0.005 kg/s, the heat was not being as effectively transferred to the tank which is at a lower temperature for this lower flow rate.

![Figure 5.22. Concrete solar collector performance with different flow rates.](image-url)
5.4.6 Tank volume

Reducing the storage volume from 65 L to 32.5 L resulted in a reduction in the SF, from 37.8% to 33.5%. The storage tank volume was reduced to identify the maximum available temperature. Although, the smaller tank did reach a higher temperature (as displayed in Figure 5.23), there was less energy available and the draw offs were subsequently greater. A smaller storage tank may work better in buildings where there are high-temperature, low-volume hot water draw-offs during the day.

![Figure 5.23. Concrete solar collector performance with different sized storage tanks.](image)

5.4.7 Initial tank temperature

The initial tank temperature for a given day largely depends on the operation of the system on the previous day, as already discussed regarding Figure 5.18. Assuming the tank was filled by the mains water at a temperature of 11 °C for March the initial tank temperature would be lower than the reference
case (initial tank temperature ≈ indoor air temperature). The resulting tank temperature profiles for these two initial tank temperature conditions are presented in Figure 5.24.

![Figure 5.24. Concrete solar collector performance with different initial tank temperature.](image)

The SF reduced from 37.8% to 33.1% when the initial tank temperature was changed from 17°C to 11°C. This reduction is due to the fact that extra heat energy is required to increase the tank temperature up to its maximum temperature of approximately 30 °C for the given day. But because of the lower starting temperature the daily efficiency increased from 30% to 36% with the system operating more efficiently with lower inlet temperatures.

Increasing the size of the tank would increase the amount of energy collected by the tank, as there would have a lower inlet temperature. However, because the energy output is equal to the mass of fluid in the tank times the temperature lift times the heat capacitance of the fluid, there would also be a smaller
temperature lift. And because the temperature lift (i.e. the increase in tank temperature over the day) is smaller for a larger tank, more auxiliary energy is required to heat the water up to application temperatures such as a shower (40 – 50 °C). This means that less energy is saved as a result of having the solar collectors. The collectors have been sized for a small building with a single person occupancy and the tank is therefore also sized for a single occupancy (i.e. approximately 65 L) where there is at least one large hot water draw off in the evening.

5.4.8 Circulating fluid and control strategy

The experimental system used water as the heat transfer fluid due to its practical advantages when compared with other heat transfer fluids. One of the disadvantages of water, however, is the risk of freezing. To overcome this in the experimental set-up a drain-back system was devised so that the water drains out of the collectors and back into the tank when there is no heat available. For other pressurised systems a 50-50 water-glycol mixture may be used, exhibiting a reduced thermal conductivity of approximately 0.42 W/mK and specific heat capacity of 3285 J/kgK. Given the reduction in SF from 37.8% for a water circulating fluid to 31.3% to a system using a 50-50 glycol water mixture, a drain back system would present a better solution to the risk of freezing than using a pressurised system with a water-glycol mixture.

In typical glazed solar thermal collector systems, the pump is only turned on once the outlet temperature is approximately 5°C higher than the tank temperature to account for losses in the pipes. In the simulated CSC system it was assumed that the tank was very closely located beside the collectors. This may not always be the case and different control strategies are therefore compared in Figure 5.25. The employment of this control strategy, compared with the current strategy used in this study resulted in a reduction in SF from 37.8% to 34% for this particular clear day. Considering the low temperature application of the CSCs, when compared with typical collectors, a lower differential temperature may be employed since the losses in the pipes would not be as significant. If the pump was set to only switch on when the outlet temperature is 2°C greater than the tank temperature, SF for that day would be 37%.
Figure 5.25. Concrete solar collector performance with different control strategies.

5.5 Conclusions of Chapter 5

A 3D model of a CSC has been developed, verified and validated. The model showed that greater outlet temperatures can be achieved by reducing the flow rate but with less energy and hence a lower tank temperature. Simulations also showed that the surface absorptance, initial tank temperature and storage tank volume all had influential effects on the performance of the CSC. The 3D model provided accurate results for the given CSC as evident by comparison with the experimental results. It is ideal for performance predictions over a small number of days. However, it does consume a significant amount of computational resources and becomes particularly computationally intensive for optimization problems and parametric sweeps. For an in-depth parametric investigation, a simpler model is required. The next chapter presents a 2D model that is adapted upon assumptions outlined in the early work of Sokolov & Reshef (1992).

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Chapter 6

Concrete Solar Collector Optimization
6 Concrete Solar Collector Optimization

A novel 3D model has been developed that accurately simulates the performance of a Concrete Solar Collector (CSC). For prototype optimization, 3D modelling requires significantly powerful computers to provide results within a sensible timeframe. A 2D model has, therefore, also been developed which significantly reduces the simulation time, while maintaining a good degree of accuracy for simple system applications. The model, presented in this section, is based on an assumption documented by Sokolov & Reshef (1992) that a 2D slice can represent a 3D concrete solar collector by neglecting the geometry in the plane perpendicular to the collector’s surface and assuming a linear temperature distribution in the direction of flow. The 2D model is solved in this work using the finite element method instead of the finite difference method, as proposed by Sokolov & Reshef (1992). The FEM allows for a more sophisticated mesh and associated accuracy. In this chapter the 2D model is developed, verified and validated (Sections 6.1 and 6.2). A reference day for which the concrete solar collector is to be compared is defined and the reference collector and system is also defined. The rationale for the day, collector and system are also provided in the text (Section 6.3). A simple system is proposed for optimization purposes so that it is only the CSC and no other system components (tank, pipes etc.) that are being assessed. The CSC is optimized for irradiance incident on a tilted surface in order to maximise temperature differences. A detailed parametric investigation is then conducted in Section 6.4 which documents the results of a total of 138 simulations. Individual parameters are investigated using a one-at-a-time approach, meaning that if one parameter is changed all other remain constant, unless explicitly stated in the text. In addition to the performance of the concrete solar collector practical limitations are also outlined to conclude the chapter.

6.1 2D model development

6.1.1 Model assumptions

The CSC is represented in this chapter by a 2D section cut, as illustrated in Figure 6.1. This 2D representation was based on the fact that the temperature gradient in the concrete parallel to the flow direction was significantly smaller than the temperature gradient perpendicular to the flow direction (D’Antoni & Saro, 2013). The real 3D volume with the embedded serpentine style pipe was converted into one long section, of length \( \Delta L \), representing the length of the pipe in the concrete. The long section was subsequently reduced to a 2D problem by assuming the temperature distribution was longitudinally linear, as per Sokolov & Reshef (1992). This conversion from a 3D to a 2D problem is displayed in Figure 6.1. The temperature distribution of the centre of the 2D section was solved by the Finite Element Method (FEM), computed in COMSOL Multiphysics 4.3.
In addition to the assumptions outlined in Table 5.1, this 2D analysis was also subject to the following assumptions:

1. The pipe layout geometry is neglected, and the concrete solar collector is represented as one long section.
2. The heat transfer coefficient between the fluid and the pipe is constant.
3. The fluid temperature is uniform for each cross section.
4. The temperature distribution is longitudinally linear.
5. There was no heat transfer at either the back or edges.

6.1.2 Model overview

The boundary conditions used in this model are the same as those applied in the 3D model from Chapter 5 (Eq. (5.8) to Eq. (5.19)); The heat conduction within the solid concrete and copper pipe is described by Eq. (6.1) i.e. Fourier’s law in 2D.
\[ \rho_c c_v \frac{\partial T}{\partial t} = k_c \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  
Eq. (6.1)

The finite element mesh for the 2D section of the CSC was generated using triangular elements with a greater number of elements produced around the pipe where larger temperature differences were expected, as shown in Figure 6.2 where the boundary conditions are also presented.

As with the 3D model, five-minute time steps were used in this model. As the boundary conditions were updated, the temperature difference throughout the solid section was updated at a rate depending on the material properties of the concrete and pipe. The solid domain was only modelled here using the FEM. The fluid was assumed to be uniform perpendicular to the flow direction. The outlet fluid temperature, \( T_o \), was determined by beginning with an energy balance:

\[ m c_w (T_o - T_i) = A_p h_f [T_{w,av} - T_{f,av}] \]  
Eq. (6.2)

where, \( m \) is the mass flow rate (kg/s), \( c_w \) is the specific heat capacity of the fluid, \( T_i \) is the inlet temperature, \( T_{f,av} \) is the average fluid temperature and \( T_{w,av} \) is the average pipe wall temperature on the
inside surface in contact with the fluid. The fluid heat transfer coefficient, $h_f$, was assumed constant throughout the simulation. The area of the wetted surface of the pipe, $A_p$, for each segment is given by Eq. (6.3).

$$A_p = \pi D_i \Delta L$$  \hspace{1cm} \text{Eq. (6.3)}

The temperature distribution was assumed to be longitudinally linear (Sokolov & Reshef, 1992), so that:

$$T_{f,av} = \frac{T_{i+} + T_o}{2}$$  \hspace{1cm} \text{Eq. (6.4)}

And rearranging equations Eq. (6.2) and Eq. (6.4) and isolating $T_o$ gives:

$$T_o = \left( \frac{n c_f - 0.5 A_p h_f}{n c_f + 0.5 A_p h_f} \right) T_{f,i} + \left( \frac{A_p h_f}{n c_f + 0.5 A_p h_f} \right) T_{w,av}$$  \hspace{1cm} \text{Eq. (6.5)}

This approximation of the outlet temperature was used to calculate the average fluid temperature which was required for the boundary condition between the fluid and pipe. The sections of the CSC, represented by 2D slices, were modelled using dynamic boundary conditions on the surfaces, depicted in Figure 6.2. The heat fluxes (gains/losses) were calculated at each time step. The heat flux between the internal fluid passing through the pipe and the 2D solid, $Q_{fいらっしゃる}$, is described by Eq. (6.6).

$$Q_{fいらっしゃる} = h(T_{f,av} - T_{p,wall})$$  \hspace{1cm} \text{Eq. (6.6)}

where the fluid temperature, $T_{f,av}$, is the average of the inlet and outlet temperatures of the section Eq. (6.4) and $T_{p,wall}$ is the average pipe wall temperature in contact with the fluid. Perfect insulation was assumed so that the heat flux at the edges and back of the collector is equal to zero.

6.1.3 Model verification

The model was first verified to determine if the assumption that modelling one long section instead of a number of combined sections was a valid assumption. The results of the verification are displayed in Figure 6.3. The error in modelling the CSC as one long section compared with eight smaller consecutive sections (coupled together by running eight simulations; using the outlet temperature of the first section as the inlet to the second and so on) resulted in a Percentage Mean Absolute Error (PMAE) of less than 1.1%.
Next the 2D model was compared to the 3D model for the 25th of March. The results are presented in Figure 6.4 and show a reasonably good correlation between both 2D and 3D models. The 2D model underestimates the outlet temperature during the heat up phase. The differences in the two model results are due to the greater number of assumptions used in the 2D model, in particular the assumption of a constant heat transfer coefficient between the fluid and pipe. A Percentage Mean Absolute Error of 2% was calculated (Eq. (5.25)) between the two model’s outlet temperatures.

Figure 6.4. Comparison of outlet temperature for 2D and 3D numerical models.

6.2 2D model validation

The 2D model is used in this chapter as part of a simple system (System (i) from Figure 5.7) operating with a low flow rate ($\dot{m} \approx 0.005$ kg/s). The 2D model was therefore validated over a course of two days.
where the system was operating at a low flow rate (as was the case for the 24\textsuperscript{th} - 25\textsuperscript{th} of January) which includes both sunny and cloudy conditions. The validation is extended to also include a day with a higher flow rate (on the 23\textsuperscript{rd} of January the flow rate $\approx 0.025$ kg/s). The flow rate was manually changed by adjusting the DAB VA 55/130 circulation pump in the evening of the 23\textsuperscript{rd} of January and the results are presented in Figure 6.5.

![Figure 6.5](image)

Figure 6.5. Experimental inlet and outlet temperature vs simulation outlet temperature of a concrete solar collector.

The Percentage Mean Absolute Error (PMAE) was used again as the validation metric, as per Ayompe et al. (2011). The simulated outlet temperature gave a PMAE of 4.7\% for the given three days. The accuracy of the 2D model is lower than the 3D model and can be attributed to the greater number of assumptions, which are presented at the end of Section 6.1.1. But given the significantly lower computational effort required, the 2D model offers a significant advantage when a large number of simulations are required, as is the case in this analysis.

The validated model was used to predict the performance of an optimally inclined (53\textdegree{} due south) low flow concrete solar collector for a clear summer day in Dublin. These conditions were selected to maximise the temperature difference between the inlet and outlet of the CSC. A constant inlet temperature of 17 °C was used, which was approximately equal to the mains water temperature for this time and location (Gill et al., 2016). The rate of useful energy output is given by Eq. (6.7).
\[ \dot{Q}_u = \dot{m}c_w(T_o - T_i) \quad \text{Eq. (6.7)} \]

which is based on the temperature difference across the collector \((T_o - T_i)\), the mass flow rate, \(\dot{m}\), and the heat capacity of the heat transfer fluid, in this case water, \(c_w\). The useful energy, \(\dot{Q}_u\), was calculated at five minute time intervals and the useful energy output per day, \(Q_{u,d}\), was calculated as the summation of the positive values of these energy outputs over a day. The daily efficiency, \(\eta_d\), can subsequently be calculated using Eq. (6.8).

\[ \eta_d = \frac{Q_{u,d}}{I_d} \quad \text{Eq. (6.8)} \]

where \(I_d\) is the total solar irradiation incident on the surface for a day. The daily efficiency, \(\eta_d\), is used as the key performance indicator of the CSCs in this chapter when comparing parameter alterations. Comparisons are made with reference to a change in the daily efficiency, \(\Delta \eta_d\), where

\[ \Delta \eta_d = \eta_{d2} - \eta_{d1} \quad \text{Eq. (6.9)} \]

or in some cases in terms of the relative change in daily efficiency, \(\Delta \eta_{d,\text{rel}}\), where

\[ \Delta \eta_{d,\text{rel}} = \frac{\eta_{d2} - \eta_{d1}}{\eta_{d1}} \times 100 \quad \text{Eq. (6.10)} \]

where \(\eta_{d1}\) and \(\eta_{d2}\) are the lower and higher daily efficiency values of two CSCs with different parameters.

6.3 System description and comparison with other absorbers

A simple system was assumed for the parametric investigation in this chapter which is only concerned with the CSC and no additional components (e.g. System (i) from Figure 5.7). An example of how this system may operate as part of a real application is displayed in Figure 6.6. The water enters from the water mains and the flow is set using a control valve. A low flow rate and ideal weather conditions were applied in the model to maximise temperature differences throughout the CSC.
The daily efficiency of CSCs is evaluated for a particularly clear day in summer in Dublin using weather data measured by Browne et al. (2016) for solar irradiance incident on a surface at an angle of 53°, as displayed in Figure 6.7.

The reference concrete solar collector was simulated using the weather inputs illustrated in Figure 6.7 and the values outlined in Chapter 5. The outlet fluid temperature, $T_o$, profile for the concrete solar collector under these conditions is displayed in Figure 6.8, in addition to other standard unglazed collector types.
Figure 6.8. Simulated performance of a concrete solar collector for a summer day in Dublin (Ireland) compared with similar copper and polymer based unglazed collectors.

A thermal lag of between approximately 5-10 minutes is observed for the CSC. A maximum outlet temperature of approximately 40 °C and a daily efficiency, $\eta_d$, of 56% were calculated for the reference CSC on a clear summer day in Dublin. For two other typical unglazed collectors, namely a 2 mm thick polymer based absorber (conductivity = 0.2 W/mK (Tsilingiris, 1999)) and a 2 mm thick copper based absorber (conductivity = 380 W/mK (BS ISO 10456, 2009)) daily efficiencies of 29% and 62% were recorded. All other geometric parameters in the comparison were kept constant, highlighting concrete as an ideal absorber material for unglazed collectors, achieving almost twice the daily efficiency of a polymer absorber. The copper unglazed solar collector recorded a slightly higher daily efficiency, but copper is significantly less durable than concrete and would degrade much earlier into its lifetime than concrete.

6.4 Parametric investigation

Values documented in the literature are reintroduced in this section to apply boundaries to the upper and lower parameter values which are compared in this section. The CSC under investigation was simulated for the range of parameter values displayed in Table 6.1.
Table 6.1. Maximum and minimum recorded parameter values and their associated reference.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter, symbol (Unit)</th>
<th>Minimum value (Reference)</th>
<th>Maximum value (Reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Parameters</td>
<td>Concrete conductivity, ( k_c ) (W/mK)</td>
<td>0.6 (Abbott, 2004)</td>
<td>4 (Keste &amp; Patil, 2012)</td>
</tr>
<tr>
<td></td>
<td>Concrete heat capacity, ( c_c ) (J/kgK)</td>
<td>655 (Kumar et al., 1981)</td>
<td>1600 (Abbott, 2004)</td>
</tr>
<tr>
<td></td>
<td>Pipe conductivity, ( k_p ) (W/mK)</td>
<td>PVC = 0.17 (Sarachitti et al., 2011)</td>
<td>Copper = 380 (Hazami et al., 2010)</td>
</tr>
<tr>
<td>Flow</td>
<td>Mass flow rate, ( \dot{m} ) (kg/s)</td>
<td>0.01 (Hazami et al., 2005)</td>
<td>0.04 (Jubran et al., 1994)</td>
</tr>
<tr>
<td>Geometric</td>
<td>Pipe Diameter, ( D_i ) (m)</td>
<td>0.01 (Sokolov &amp; Reshef, 1992)</td>
<td>0.0254 (D’Antoni &amp; Saro, 2013)</td>
</tr>
<tr>
<td></td>
<td>Pipe plane depth, ( D_{emb} ) (m)</td>
<td>0.01 [minimum for this collector]</td>
<td>0.07 [maximum for this collector]</td>
</tr>
<tr>
<td></td>
<td>Pipe Spacing, ( D_s ) (m)</td>
<td>0.04 (Sokolov &amp; Reshef, 1992)</td>
<td>0.165 (D’Antoni &amp; Saro, 2013)</td>
</tr>
<tr>
<td></td>
<td>Panel thickness, ( \delta ) (m)</td>
<td>0.02 (Keste &amp; Patil, 2012)</td>
<td>0.127 (D’Antoni &amp; Saro, 2013)</td>
</tr>
<tr>
<td>Surface properties</td>
<td>Absorptance, ( \alpha )</td>
<td>0.6 (Sarachitti et al., 2011)</td>
<td>0.91 (Al-Saad et al., 1994)</td>
</tr>
</tbody>
</table>

The values are based on either the maximum/minimum values found in the CSC literature or, if relevant, practical maximum/minimum values. The individual parameters’ (listed in Table 6.1) effect on the performance of a CSC is presented in this section with reference to the daily efficiency (on a clear day in summer), \( \eta_d \), predicted by the validated 2D FE model. Thermal images of the central section of the CSC at 2.00PM are displayed for different values of the individual parameter under investigation. The temperature scale is adjusted for each figure to emphasize the visual information from the 2D sections. Results from a total of 138 simulations of combinations of parameters are presented in the subsequent sections.

6.4.1 Concrete conductivity

Thermal conductivity values found in the CSC literature range between 0.6 (Abbott, 2004) and 4 W/mK (Keste & Patil, 2012). Measured concrete conductivity values found in this research (Chapter 3) ranged from 1.4 W/mK to 2.06 W/mK. Both ranges are displayed in Figure 6.9 with the range of measured values highlighted by the grey region.
Figure 6.9. Daily efficiency vs. concrete conductivity along with 2D thermal section cuts for a selection of conductivity values (indicated by the dotted arrows) taken at 2.00PM.

Increasing the thermal conductivity, $k_c$, of the concrete increases the daily efficiency of the CSC, $\eta_d$, with a trend of diminishing returns. Closely spaced thermal contours between the surface and the pipe are observed for low $k_c$ values (Figure 6.9 (top)). Because of this, more heat is lost to the surroundings before it could be effectively transferred to the pipes, ultimately resulting in a lower efficiency. Greatest improvement in daily efficiency occurs when increasing the conductivity from smaller values. For example, increasing the thermal conductivity from 0.5 to 2 W/mK increases the daily efficiency from 47% to 57% ($\Delta \eta_d = 10\%$) while further improving the concrete conductivity from 2 to 4 W/mK only increases the daily efficiency by an additional 2% (i.e. from 57% to 59%).

A daily efficiency of 54.4% was calculated for a CSC constructed with the ‘reference’ concrete mixture ($k_c = 1.4$ W/mK Chapter 3). Replacing the standard limestone aggregate of this mixture with quartzite improves the daily efficiency to 55.6%. For small efficiency gains, replacement is justified only if the alternatives are matched on price and availability. Incorporating steel fibres in the mixture further improved the daily efficiency by an additional 0.9%, but this inclusion is costly and the additional cost of the high dosage of steel fibres would not warrant the improved performance.
6.4.2 Specific heat capacity

The specific heat capacity, $c_s$, of concrete is one of the unique characteristics of concrete solar collectors. Because of this, thermal slices are displayed during both the heat-up (morning) and cool down phases of the day in Figure 6.10.

Figure 6.10. Daily efficiency vs. concrete specific heat capacity along with 2D thermal sections for a selection of specific heat capacity values during morning heat up and evening cool down phases.

Increasing the specific heat capacity from 655 J/kgK (Kumar et al., 1981) to 1600 J/kgK (Abbott, 2004) reduced the daily efficiency by less than 2%. While the same amount of energy is absorbed by the surface of the CSC, a higher heat capacitance results in a lower efficiency because more heat is temporarily stored in the concrete. Some of this heat is used later in the day but some is also lost to the environment, therefore more temporarily storage means more potential heat loss. The thermal sections in Figure 6.10 (during heat up phase) show how more heat enters the concrete with lower specific heat capacitance than concrete with higher heat capacitance values. But the sections in Figure 6.10 (during cool down phase) also highlight how more heat is available later in the day for these CSCs with higher heat capacitance values.
The daily efficiency as a single numeric result does not fully present the effect of the heat capacitance. Figure 6.11 highlights the dynamic behaviour of two CSCs with different specific heat capacities. It shows how the slower heat up of a CSC with a higher specific heat capacity is somewhat made up for later in the day due to its slower cool down. While both CSCs have similar daily efficiencies, their dynamic response was quite different. This increased energy output later in the day may be advantageous for very specific systems and load profiles. For example, concrete mixtures with higher heat capacitance values are advantageous for CSCs installed as a system without any hot water storage tank and with thermal energy loads only in the evening.

![Outlet temperature profiles for two CSCs with different specific heat capacities on the 5th of July.](image)

6.4.3 Concrete thickness

The thickness of the CSC is also a unique characteristic. It is examined here by increasing the amount of concrete behind the pipe so as not to be mixed up with the pipe embedment depth which is another parameter. The thickness of the CSC has heat capacitance effects, Figure 6.12 therefore displays the energy output after 6.00PM as well as the daily efficiency. Increasing the panel thickness from 0.03 m (smallest thickness for given collector) to 0.127 m (D’Antoni & Saro, 2013) reduced the daily efficiency by less than 3%.
Figure 6.12. Daily efficiency and energy output vs. panel thickness along with 2D thermal section cuts for a selection of panel thickness values taken at 2.00PM.

The thicker thermal sections display a greater area for heat to be temporarily stored. This heat is not all reused and some is lost to the environment before it can be reused resulting in an overall less efficient CSC. Ideally the CSC would be as thin as practically possible. However, an increased thickness resulted in a greater energy output in the evening. The reduction of the concrete thickness in cladding systems using high performance concrete mixtures is the focus of ongoing research (Hyde & Kinnane, 2016). Future concrete cladding elements are expected to use much less concrete and thereby embody less energy, which also could portray a benefit for CSCs.

6.4.4 Pipe conductivity

A number of pipes of varied material ranging from low conductivity plastics, such as PVC \( (k_p = 0.17 \text{ W/mK}) \), to conductive metals, such as copper \( (k_p = 380 \text{ W/mK}) \) are documented in the literature. The daily efficiency, \( \eta_{d} \), is compared for CSCs with different pipe types and their associated conductivity values in Figure 6.13.
Similar to the concrete conductivity, the daily efficiency, $\eta_d$, increases as the pipe conductivity increases. The greatest efficiency increases are observed at lower thermal conductivities. $\Delta \eta_d = 5\%$ for an increase in $k_p$ from 0.17 to 2 W/mK while $\Delta \eta_d = 1.5\%$ for an increase in $k_p$ from 2 and 380 W/mK.

The thermal section cuts (Figure 6.13 (top)) for the plastic pipes (PVC and PEX) show how the concrete reaches a higher temperature because the heat is not transferred to the internal fluid as efficiently as those collectors using metallic pipes. The difference in the energy output between different types of metal is negligible ($\Delta \eta_d < 0.5\%$). The decision should be determined by the pipe’s resistance to corrosion and cost rather than the conductivity of the pipe.

Plastic pipes require greater spacing for a serpentine set-up compared with copper pipe. This gives copper piping an additional advantage for smaller sized CSCs since a greater length of pipe can be fitted into a smaller area. For larger sized CSCs plastic pipe is a more cost effective and durable option. PEX pipe is currently the pipe of choice for the underfloor heating market because of its superior resistance to corrosion, lower cost and lower susceptibility to leaks.

Figure 6.13. Daily efficiency vs. pipe conductivity along with 2D thermal section cuts for a selection of pipe conductivity values taken at 2.00PM.
Another option would be to omit the pipe altogether and cast pipe channels using dissolvable forms or similar. With concrete having a thermal conductivity of between 1 and 2 W/mK the efficiency of such a design may be assumed similar to a CSC with a metallic pipe.

6.4.5 Pipe spacing

The pipe spacing was defined as the width of each 2D section (approximately representing the distance between each parallel pipe of a real set up). The closer the pipes are spaced together the longer the overall length of pipe for a given concrete collector area. Because the panel area remains constant during the analysis, the section length, \( \Delta L \), was adjusted in the model for a change in the pipe spacing (e.g. for a spacing of 0.1 m the section length is equal to 10 m while a spacing of 0.05 m would be associated with a 20 m length of pipe). The increase in daily efficiency is displayed for a range of pipe spacing values found in the literature in Figure 6.14.

![Figure 6.14](image)

> Figure 6.14. Daily efficiency vs. pipe spacing along with 2D thermal section cuts for a selection of pipe spacing values taken at 2.00PM.

There is an approximate linear increase in daily efficiency, \( \eta_d \), of an additional 2.7% for every 0.02 m reduction in the spacing for the range of values found in the CSC literature (\( D_s = 0.04 - 0.165 \) m). For example, reducing the spacing between the pipes from 0.1 to 0.08 m increased the daily efficiency from 48.8% to 51.5%.

Thermal images highlight the area of uncaptured heat for the larger pipe spacing (\( D_s = 0.160 \) m) with temperatures reaching as high as 46.3 °C. More of this stored heat will be lost to the environment before
it can be extracted from the pipes when compared with closer spaced pipes which extract the heat more efficiently. Temperatures do not exceed 36°C for the section cut of the collector for $D_s = 0.04$ m.

The temperature profiles, at first look, seem counterintuitive but the sections are all taken halfway throughout the pipe flow path and the lower temperature distribution for the closer pipe spacing is made up in the end by the longer length of pipe. For example, the fluid in the section for $D_s = 0.04$ m still has to travel an additional 12.5 m within the CSC, compared with an additional 3.125 m for the section for $D_s = 0.04$ m.

### 6.4.6 Pipe diameter

The pipe diameter is usually dictated by the available standard pipe dimensions and only a small range of pipe diameter values are found in the CSC literature. The daily efficiency, $\eta_d$, for CSCs with various pipe diameters is displayed in Figure 6.15. The pipe diameter is changed here without changing the central plane of the pipe, following D’Antoni & Saro (2013).

![Figure 6.15. Daily efficiency vs. pipe diameter along with 2D thermal section cuts for a selection of pipe diameter values taken at 2.00PM.](image)

The change in daily efficiency, $\eta_d$, for the range of pipe diameter values taken in the literature (i.e. $D_i$ between 0.01 and 0.025 m) is 6.6% (from 52.8% to 59.4%). The increase in performance, with increasing pipe diameter may be associated with the greater surface area of the heat exchanger, as per
Eq. (4.11). The thermal sections with the larger diameter pipes display a cooler concrete, representing a more efficient heat extraction by the fluid in the pipe.

Smaller pipes are more typical of standard solar thermal technologies as they are a more cost effective option. The option to omit the pipe altogether and use concrete channels is again an interesting option because increasing the diameter of the pipe would not affect the cost. But increasing the diameter and reducing the depth of the channel below the surface would create thinner concrete sections between the fluid and surface of the CSC and therefore be restricted by structural limitations. The greater diameter is also positively affected by the amount of the pipe closer to the surface. This may be described in better detail by assessing pipe embedment depth, $D_{emb}$.

### 6.4.7 Pipe depth

The location of the centre line of the pipes from the exposed surface is referred to here as the embedment depth, $D_{emb}$. The influence of embedding the pipe deeper into the concrete is investigated in Figure 6.16.

**Figure 6.16.** Daily efficiency vs. pipe embedment depth along with 2D thermal section cuts for a selection of pipe embedment depth values taken at 2.00PM.
There is an approximate linear increase in daily efficiency of $\Delta \eta_d = 5\%$ for every 0.02 m closer the pipes are located to the surface. For example, burying the pipes at a depth of 0.05 m results in a daily efficiency of 48% compared with an efficiency of 53% for an embedment depth of 0.03 m.

The thermal sections (Figure 6.16 (top)) show temperatures ranging from 36 °C on the surface to 33 °C at the bottom/back of the CSC with an embedment depth, $D_{emb}$, of 0.01 m. Temperature ranges from 43 °C on the exposed surface to 28.6 °C at the bottom/back of the CSC with an embedment depth, $D_{emb}$, of 0.07 m. Locating the pipes further from the surface means the heat is not as efficiently extracted from the concrete. For pipes located deeper in the concrete the importance of the thermal conductivity of the concrete becomes even more apparent. This interdependence between pipe depth and concrete conductivity is displayed in Figure 6.17.

![Figure 6.17. Interdependence between the pipe plane depth and concrete conductivity in relation to the daily efficiency.](image)

The embedded pipe is not a structural element nor is copper (and even less so plastic) as susceptible to corrosion as steel and therefore rigorous standards that exist for determining the cover of steel rebar (IS EN 206-1, 2002) are not required. But valuable insight can be taken from this standard practice, for which the depth of the rebar is designed based on the surrounding environment (exposure conditions). Revealing the copper pipe at the surface or locating the pipe too close to surface reduces the CSC’s durability which is one of its primary advantages when compared with metallic based solar thermal collectors. Additionally, a shallow embedment depth comes with a greater risk of spalling and loss of
concrete. The unappealing appearance of an exposed pipe, particularly if located on the façade, is a drawback of exposing the pipe through the concrete. The pipes should therefore be located as close to the surface as is practically feasible.

6.4.8 Absorptance

The absorptance has been identified as one of the most influential performance parameters. The daily efficiency of a CSC is calculated for different surface absorptance values and displayed in Figure 6.18. Reference is made to both the experimentally measured absorptance values (grey area) from Chapter 3 as well as other values recorded in the literature.

![Figure 6.18. Daily efficiency vs. absorptance along with 2D thermal section cuts for a selection of absorptance values taken at 2.00PM.](image)

A strong linear increase in daily efficiency of 6% is shown per 0.1 increase in absorptance, \( \alpha \). This increase is comparable to changing from a concrete with red pigment (\( \eta_d \approx 50\% \)) to a plain concrete painted black (\( \eta_d \approx 56\% \)). Thermal section cuts of the CSCs show how those with higher absorptance values can achieve a much higher temperature because very little of the solar radiation is reflected.

Simply painting the surface of plain concrete with standard black outdoor paint increases the daily efficiency from 42\% (\( \alpha = 0.71 \)) to 56\% (\( \alpha = 0.94 \)). This is an improvement equivalent to one third of its original daily efficiency (or \( \Delta \eta_{d,rel} = 33\% \)). The yellow coloured finish has the same daily efficiency as the plain concrete given its similar absorptance values. A compromise between aesthetics and performance may be required regarding the absorptance. For example, a 3\% downgrade in performance from 56\% (for black paint) to 53\% (black pigment finish) would be considered acceptable because of the better appearance of the black pigment concrete.
6.4.9 Emittance

The other surface property influencing the CSC performance is the thermal emittance. A range of emittance values was not available in the CSC literature, instead a value of 0.9 is common to most studies that used a black concrete (Blecich & Orlić, 2012; D’Antoni & Saro, 2013; Tanzer & Schweigler, 2016). However, the daily efficiency of a theoretical CSC is analysed here for a range of emittance values considering the potential of spectrally selective coatings, which have already been developed for other metallic based solar thermal technologies (Dudita et al., 2014; Orel & Gunde, 2001). These are coatings with a high absorptance in the solar range of wavelengths and a low emittance in the infrared range. To date there is a paucity of research on spectrally selective coating research applicable to concrete. Figure 6.19 provides an insight into how a spectrally selective coating of a CSC would perform.

![Figure 6.19. Daily efficiency vs. emittance along with 2D thermal section cuts for a selection of emittance values taken at 2.00PM.](image)

A linear increase in daily efficiency of 1.5% is shown per 0.1 decrease in the thermal emittance, \( \varepsilon \). The thermal images of the 2D sections show less heat being lost to the surrounding for the lower emittance surfaces. Replacing a typical black paint \( (\varepsilon \approx 0.9) \) with a spectrally selective black paint \( (e \approx 0.1) \) increases the daily efficiency from \( \eta_d = 56\% \) to \( \eta_d = 69\% \). This potential increase in daily efficiency of 13% highlights spectrally selective coatings as an area of CSCs worth exploring further.

6.4.10 Mass flow rate

The flow rate of a solar thermal system is typically optimized for the specific system and pump rather than the specific type of collector. A low flow rate of 0.005 kg/s was used as the reference flow rate in
this study to maximize the temperature difference across the CSC. Other advantages of low flow rate systems are documented in the literature, such as improved stratification in the connecting storage tank (Cristofari et al., 2003; Notton et al., 2014). Higher flow rate values are investigated in Figure 6.20 with reference to both the daily efficiency and the maximum outlet temperature.

![Figure 6.20. Daily efficiency and maximum temperature outlet vs. mass flow rate.](image)

When the electricity consumption of the pump is neglected, increasing the flow rate results in an increase in the daily efficiency while the maximum outlet fluid temperature reduces. Omitting the pump from the calculations (as per Figure 6.20) reveals how doubling the flow rate from 0.005 to 0.01 kg/s increases the daily efficiency by an additional 7%. For a similar 0.005 kg/s increase in the mass flow rate from 0.035 to 0.04 kg/s results in no significant increase in the daily efficiency. The results in Figure 6.20 also consider the influence of two different pumps (a 10% efficiency pump and a 2% efficient pump). When the energy consumption of the pump is offset against the available thermal energy it becomes evident that higher flow rate consume a greater amount of electrical energy and an optimization problem arises. The returns on the energy output diminish at a rate depending on the pump used and head loss of the system. For the given system and pump, optimum performance is achieved for flow rates between 0.015 kg/s and 0.025 kg/s.

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6.5 Parametric summary

The range in the daily efficiency between the parameter minimum and maximum values are displayed by the black bars presented in Figure 6.21.

The greatest daily efficiency changes, \( \Delta \eta_d \), are observed for the absorptance (\( \Delta \eta_d = 18.6\% \)), the pipe spacing (\( \Delta \eta_d = 16.3\% \)) the pipe embedment depth (\( \Delta \eta_d = 14.8\% \)) and the concrete conductivity (\( \Delta \eta_d = 11.7\% \)) for the range of parameter values found in the CSC literature. The specific heat capacity and the panel thickness are the least influential parameters, with no change in daily efficiency, \( \Delta \eta_d \), greater than 1.3\% for the given range of values.

6.5.1 Practical limitations

The limitations of each parameter value can be categorised as being an economic, practical or aesthetical limitation. These limitations are summarised in Table 6.2. Considering both the performance results and limitations, the concrete thermal properties and the surface properties provide most scope for improvement. While some of the geometric parameters, namely the pipe embedment depth and pipe spacing, displayed a significant influence on the performance they are limited by practical constraints. Having a higher thermal conductivity becomes more important for the CSC as the pipes are located further away from the surface because the heat needs to travel a greater distance to the pipe.
Table 6.2. Model variables and associated practical limitations for building integration.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter, symbol (Unit)</th>
<th>Cost</th>
<th>Practicality</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Parameters</td>
<td>Concrete conductivity, $k_c$ (W/mK)</td>
<td>€ can &gt; as $k_c$ increases because of costly additives.</td>
<td>Good workability required for pipe to concrete bond.</td>
<td>Cement type and additions generally dictates surface finish.</td>
</tr>
<tr>
<td></td>
<td>Concrete heat capacity, $c_c$ (J/kgK)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipe conductivity, $k_p$ (W/mK)</td>
<td>Copper &gt; € but also better performance.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric</td>
<td>Pipe Diameter, $D_i$ (m)</td>
<td>$&gt; D_i = &gt;$ € but better performance.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipe plane depth, $D_{pvs}$ (m)</td>
<td></td>
<td>Should be deep enough to minimize spalling and loss of concrete.</td>
<td>Surface protruding pipes possible, but negatively impact aesthetics and durability.</td>
</tr>
<tr>
<td></td>
<td>Pipe Spacing, $D_s$ (m)</td>
<td>$&gt; D_s = &gt;$ €.</td>
<td>Copper pipes allow for closer spacing.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Panel thickness, $\delta$ (m)</td>
<td>$&gt; \delta = &gt;$ volume $\therefore &gt;$ €.</td>
<td>Thick enough to ensure adequate strength for the given purpose.</td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>Mass flow rate, $\dot{m}$ (kg/s)</td>
<td>$&gt;\dot{m} = &gt;$ $\therefore &gt;$ €.</td>
<td>$&gt;\dot{m}= $ higher pressure in wall $= &gt;$ likelihood of leaks.</td>
<td></td>
</tr>
<tr>
<td>Surface properties</td>
<td>Absorptance, $\alpha$</td>
<td></td>
<td>Durability issues with coatings and paints.</td>
<td>CSC’s most suitable if dark shades of concrete are used.</td>
</tr>
<tr>
<td></td>
<td>Emittance, $\varepsilon$</td>
<td>Selective coatings would increase the cost.</td>
<td>Durability issues with coatings and paints.</td>
<td></td>
</tr>
</tbody>
</table>

- € = cost
- $> =$ increase
- $\therefore =$ therefore

Outlet temperatures are plotted in Figure 6.22 for the reference CSC, a CSC using typical concrete, a CSC with optimised concrete as well as a CSC with an optimized geometry neglecting any of the practical limitations discussed in Table 6.2. The associated parameters for these collectors are displayed in Table 6.3.
Table 6.3. Parameter values for the optimum concrete solar collectors.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter, symbol (Unit)</th>
<th>Standard collector</th>
<th>Surface and material optimum parameters</th>
<th>Surface, material and geometric optimum parameters (disregarding practical limitations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>“Standard”</td>
<td>“Practically optimum”</td>
<td>“Theoretically optimum”</td>
</tr>
<tr>
<td><strong>Material Parameters</strong></td>
<td>Concrete conductivity, $k_c$ (W/mK)</td>
<td>1.27</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Concrete heat capacity, $c_c$ (J/kgK)</td>
<td>800</td>
<td>655</td>
<td>655</td>
</tr>
<tr>
<td></td>
<td>Pipe conductivity, $k_p$ (W/mK)</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td><strong>Geometric</strong></td>
<td>Pipe Diameter, $D_i$ (m)</td>
<td>0.015</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>Pipe plane depth, $D_{emb}$ (m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>Pipe Spacing, $D_s$ (m)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Panel thickness, $\delta$ (m)</td>
<td>0.08</td>
<td>0.08</td>
<td>0.029</td>
</tr>
<tr>
<td><strong>Surface properties</strong></td>
<td>Absorptance, $\alpha$</td>
<td>0.71</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Emittance, $\varepsilon$</td>
<td>0.9</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The benchmark CSC’s parameters were selected based on a combination of experimental measurements, practical reasoning and estimates based on values found in the literature. From this selection process alone an increase in performance of 15% is observed when compared with that of an unpainted standard concrete mixture (from $\eta_d = 40.4\%$ to $\eta_d = 55.7\%$). Additional material enhancements (as per Table 6.3) increase the performance by another 16% (from $\eta_d = 55.7\%$ to $\eta_d = 71.7\%$). Achieving these surface and thermal concrete properties of this CSC would be costly.

Theoretically optimizing the geometry, without considering any practical or economic limitations, further improved the daily efficiency by an additional 4% (from $\eta_d = 71.7\%$ to $\eta_d = 75.7\%$). However, for this ‘optimized geometry’ it is arguably no longer a CSC and rather a costly series of large diameter, very closely spaced, copper pipes with some concrete poured around them.
Figure 6.22. Daily Outlet temperature profiles of concrete solar collectors using optimum parameters along with 2D thermal section cuts for the associated concrete collectors at 2.00PM.

6.5.2 Concrete solar collector design guidelines

Based on the performance and practical conclusions, design guidelines for a concrete solar collector are described in the following steps.

1. Use locally sourced materials to construct a well compacted concrete that would increase the conductivity of the concrete mixture without increasing the cost. The depth of pipe should be at least greater than the minimum aggregate size so maximum aggregate size of 10mm is suggested.
2. Even though PEX piping is less conductive, the reduction in performance were not shown to be so significant. Due to its superior durability, it is therefore advised for building integrated concrete solar collectors where potential leaks would be a more difficult issue to deal with. For roof mounted concrete solar collectors with minimal roof space copper pipes could be used to minimise the pipe spacing.

3. The pipes should be embedded as close as possible to the surface while abiding by aesthetical and structural constraints. If the concrete solar collectors are not in the view of the public exposing the pipes may be desirable, however, over exposure to sunlight reduces the durability of the pipe and hence lifetime of the collector.

4. Dark surface finishes should be used where applicable and can be achieved by using pigment in the concrete for a more appealing surface finish and lower maintenance than paint. Spectrally selective coatings would also be desirable if applicable to concrete without significantly increasing cost or reducing the lifetime.

5. The mass flow rate of the system can be adjusted and as with typical solar thermal installations should be optimised according to the system.

6.6 Conclusions for Chapter 6

The 2D model provides an efficient tool for multiple parametric simulations. The pipe depth, pipe spacing, surface absorptance and concrete conductivity have been highlighted as those design parameters having the greatest impact on the performance. However, these parameters are often bound by practical, economic or aesthetical limitations which need to be considered in the design of the CSC.

One limitation of 2D models is that other components of a system cannot be implemented in the model using the same software package. This is due to the dependence of the inlet fluid boundary condition on both $T_o$ and $T_i$ and the subsequent resulting non-linearity of the system of equations if another component were to be implemented. To model a system similar to that described in Chapter 5, an additional software, such as MATLAB, would need to be combined with the COMSOL model using a server. This is possible, but it results in significantly larger simulation times with information inefficiently being passed between each program at every time step. The low computational effort of the 2D model is one of its primary advantages and integrating it with another software compromises this advantage.
Chapter 7

Applications and Economics
7 Applications and Economics

This chapter investigates the real applicability and economic potential of a Concrete Solar Collector (CSC) that has been practically optimized following the design guidelines that conclude Chapter 6. The primary objective of this chapter is to identify the building, façade, hot-water-system and climate typologies that are best suited for CSCs, and to subsequently investigate their performance and economic viability. Section 7.1 summarises the CSC systems used in this thesis and proposes other potential CSC systems for future work; the section provides a critical assessment of each system. A review of different buildings and their associated hot water consumption is then presented in Section 7.2 to better realise those buildings suitable for façade integrated solar thermal technologies. A conceptual design of building integrated CSCs for precast concrete cladding systems is presented in Section 7.3, focusing on building aesthetics and construction details. In Section 7.4 the energy output and solar fraction of a practically optimised CSC is estimated for four European climates (Dublin, Seville, Helsinki and Sofia) using the detailed 3D model from Chapter 5. Finally, in Section 7.5, the individual costs of the CSC system components are documented and combined; the savings from replacing different fuel sources are offset from the initial cost of the CSC system and are used to calculate the payback period for the different climates.

7.1 Concrete solar collector systems

CSCs have shown promise for low temperature hot water applications, such as preheating for Domestic Hot Water (DHW). The experimentally tested system (System (ii)) and numerically simulated systems (System (i – iv)) are illustrated in Figure 7.1. System (i), which is used in the parametric investigation in Chapter 6, provides a useful system for characterising the performance of the CSC as it only contains the CSC itself and no other components. System (ii), which is representative of the experimental set-up investigated in Chapter 4, contains the critical components of a drain-back system and provides a useful means for experimental measurement without the need to dump and waste water. System (iii) is simulated in Chapter 5 and includes a controller to operate the pump only when the temperature of the fluid in the CSC is greater than the tank temperature. System (iv), also simulated in Chapter 5, is representative of a real preheating system; it is also used in this chapter for the further investigation of the practically optimized CSC in other European climates.
In addition to the four systems investigated in this study (i to iv) other, more complex, CSC systems could be installed. An example of four of these potential systems is presented in Figure 7.2 (v to viii).

In Systems (i) to (iv), to protect against freezing the CSCs are installed at an elevation higher than the water tank so that when the pump is switched off the water from the CSCs drain-back into the tank. Using the classical pressurised glycol system to overcome freezing requires the addition of heat exchangers to separate the potable water from the glycol-water mixture. Systems (v) to (viii) employ this type of system. Building designers typically encourage this type of system due to its apparent lower risk of freezing, however it comes at a significant cost due to the extra components required. Additionally, the thermal performance is reduced due to the sub-optimal properties of water-glycol mixtures when compared with potable water.

Figure 7.1. Concrete solar collector systems tested and modelled in this thesis (i to iv).
System (iv) and System (v) present two different ways of topping up the preheated water for domestic hot water applications. System (iv) heats the water at a point directly before use, similar to an electric shower, while System (v) heats the water in the tank using the auxiliary source; this is the typical method of heating standard domestic hot water storage tanks and the CSC is only an additional preheating component of an already established DHW system.

System (vi) consists of a concrete solar collector used in conjunction with a heat pump and is used for space heating applications. This would be a suitable set-up for a façade integrated CSC given the vertical orientation of the CSC which captures more irradiance in winter than low angle tilted collectors. A buffer storage tank is used in System (vi) to separate the two circulation loops. The two separate loops of System (vi) mean complex modelling techniques are required for system simulation that require the coupling of two or more software packages; namely a FEM-CFD software for the CSC itself (e.g. COMSOL Multiphysics) and an energy systems software for the system (e.g. TRNSYS) as well as a host/server to ensure data exchange between both programs (e.g. MATLAB). Such a set-up would be computationally inefficient and dramatically increase the simulation time of an already time-consuming...
model. A better option may be to produce a simple model for complex systems. Investigation of these is proposed for future research.

With Systems (vii) and (viii) a pump is not required. For System (vii) the internal piping system should be constructed with parallel vertical pipes connected to header pipes and the tank should be elevated above the collectors to allow for natural convection. These cheap thermosiphon systems are popular in warmer climates where freezing is not a risk. System (viii) is possibly the simplest of all the systems and involves no additional components other than the concrete solar collector itself. An auxiliary heater would be required for DHW applications. But this system could also be implemented as a cheap outdoor shower system or swimming pool heater.

7.2 Building typologies

The hot water consumption and geometry of different building types determine the applicability of CSCs. Different building geometries and functionalities are therefore assessed here.

7.2.1 Building hot water consumption

There are many variables that determine the Hot Water Consumption (HWC) of different buildings. These variables include the building’s function and occupancy pattern, as well as the largely varying behaviour of the occupants themselves. As a result, it is difficult to accurately predict the hot water demands of individual buildings. Instead of measuring the exact hot water consumption of individual buildings, this section aims to document the average hot water consumption of different building typologies.

According to the National Standards Authority of Ireland (NSAI S.R. 50-2, 2012), the HWC of a residential dwellings is equal to 28 litres plus an additional 26 litres per number of occupants \( N \); i.e. the HWC is a linear function of the number of occupants (NSAI S.R. 50-2, 2012). Studies in other countries have also quantified the HWC of residential buildings (Lutz et al., 1996; Evarts & Swan, 2013; Meyer & M Tshimankinda, 1998; Meyer & M. Tshimankinda, 1998; Energy Saving Trust, 2008; BRE Housing centre, 2005). While there is a paucity of information on the HWC of residential buildings, there is an even greater deficiency of information regarding the HWC of non-residential buildings. A review has been conducted on the limited number of studies that do examine the HWC of these different buildings, namely hotels, hospitals and offices. The HWC of all these buildings are also documented in Table 7.1 based on a litre per capita per day (Lcd) basis.
Table 7.1. Hot water consumption in Litres per capita per day (Lcd)

<table>
<thead>
<tr>
<th>Publication</th>
<th>Country</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Canada</td>
<td>2013</td>
<td>(Evarts &amp; Swan, 2013)</td>
</tr>
<tr>
<td></td>
<td>Ireland</td>
<td>2012</td>
<td>(NSAI S.R. 50-2, 2012)</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>2012</td>
<td>(NREL, 2012)</td>
</tr>
<tr>
<td></td>
<td>U.S.</td>
<td>2011</td>
<td>(Bujak, 2010)</td>
</tr>
<tr>
<td></td>
<td>Poland</td>
<td>2010</td>
<td>(Energy Saving Trust, 2008)</td>
</tr>
<tr>
<td></td>
<td>U.K.</td>
<td>2008</td>
<td>(Rankin &amp; BRE Housing centre, 2005)</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>2006</td>
<td>(Meyer &amp; M Tshimankinda, 1998)</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>1998</td>
<td>(Meyer &amp; M Tshimankinda, 1998)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building type</th>
<th>House/Apartment</th>
<th>Hotel</th>
<th>Hospital</th>
<th>Office</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>65 28+26N¹</td>
<td>76</td>
<td>197</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>36+25N¹</td>
<td></td>
<td>111-124</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60 40+28N¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>49 56-66</td>
<td>65-110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N¹ refers to the number of occupants. A number of studies describe the HWC as a function of N, rather than in Lcd. SA: South Africa

Some of the data from the studies was obtained using measured data from real buildings (Bujak, 2010; Energy Saving Trust, 2008; Rankin & Rousseau, 2006; Meyer & M Tshimankinda, 1998; Meyer & M Tshimankinda, 1998) while the other results were obtained via a survey based study (Evarts & Swan, 2013; NREL, 2011; BRE Housing centre, 2005). It is clear from Table 7.1 that hotels, hospitals and apartments consume the most hot water and are therefore best suited for facade integrated CSCs.

7.2.2 Building geometry

For larger building a myriad of different complex systems exists, but for the sake of analysis here the apartments are considered to have their own individual systems. Increasing the roof to façade area ratio, and hence roof to living space ratio, reduces the necessity for façade located solar collectors. Different building geometries are presented in Figure 7.3.
Therefore, a stronger case, for solar collectors to be installed on the façade of buildings, based on limited roof space, can be made for medium to high-rise buildings. An example building Figure 7.4, Liberty Hall, located on Eden Quay, Dublin 1, is considered in this section with reference to the characteristic loads of the buildings documented in Table 7.1. While this building is considered as a high-rise building in Dublin, it would be considered as a typical mid-rise building in many major cities around the globe.

If this building were to function as a block of flats or apartments the population of the building must first be estimated. A typical apartment block for a one bedroom dwelling should have a floor area of 50 m² with a 3 m high storey (Government of Ireland, 2015). Given the dimensions of the case study building, six one-bedroom apartments could be planned for each floor, giving a total of 102 apartments, assuming there is one person per bedroom. The HWC of each apartment block may be somewhere
between 49 and 68 Lcd, i.e. the lower and upper limits from Table 7.1. Using these figures as lower and upper limits respectively, a building of this size would consume between 5,500 and 6,950 litres of hot water per day. For application temperatures of 52°C (as per Chapter 4), this equates to a total energy consumption of between 265 - 340 kWh every day, for hot water alone.

For this building to function as a hotel, an estimation of the number of rooms for the given floor area must be made. The total floor area of this building would not be covered entirely by bedrooms. A hotel design, planning and development guide suggests that there should be sufficient space to provide for other areas such as meeting rooms and reception area (Penner et al., 2013). Furthermore, another planning guide for hotels suggests that 90% of economy or budget hotels floor space is allocated for rooms, while for business class hotels this is estimated to be approximately 70% (deRoos, 2011). An average hotel is considered here, so it is assumed that 80% of the floor area is used for bedrooms. A further assumption is required in order to estimate the number of occupants; an occupancy density value of 0.05 people/m² is taken (NCM, 2007). This results in a population of 208 for this hotel. From the literature (NREL, 2011; Rankin & Rousseau, 2006) it was concluded that the HWC ranges from 76 - 110 Lcd. This results in the total HWC ranging from 15,800 to 22,900 Lcd; in terms of energy this equates to between 770 and 1,120 kWh every day.

Hospital buildings vary considerably from one to the other in terms of their function, hence, in their HWC also. This paper aims to obtain a general idea of the HWC of a hospital building. As a result, an assumption is made that 40% of the floor area is allocated to bedrooms and an occupancy density of 0.105 per/m² is taken (NCM, 2007). The literature review found that the consumption of hot water ranges from 111 – 197 Lcd (Bujak, 2010; NREL, 2011). Hospitals are large consumers of hot water and could be an ideal location for all solar thermal technologies. In this case, the range in HWC is between 24,200 and 43,000 Lcd (1,180 – 2,100 kWh every day).

Offices consume the least amount of hot water per m² of floor area. An assumption that 95% of the floor area of the building is allocated to offices is made, leaving the remaining area for corridors and reception areas where an occupancy density of 0.095 per/m² is used (NCM, 2007). There is a paucity of information on the HWC of office buildings, probably due to its low impact on the total energy consumption of the building. It is suggested that an occupant of an office uses 4 litres of hot water per day resulting in a total of 469 litres of hot water per day for this building (NREL, 2011).

It is the apartment building that is considered in greatest detail in this thesis because the apartment blocks can be assessed individually and because precast concrete is a common cladding choice for this building typology. A conceptual image of where a CSC, acting as part of a concrete clad apartment block, may be installed is displayed in Figure 7.5. The image highlights how a modular CSC could fit
seamlessly as part of a precast cladding system. Precast concrete cladding is a well-established market which already has its own standards and guidelines (Bryden et al., 2002). Assuming the width of an individual block is 5 m and one third of the exposed façade is transparent (Figure 7.5), the remaining opaque area is 10 m², of which 2 m² may be attributed to CSCs. It was found in Chapter 5 that the maximum temperature was achieved after approximately 2m², for the given pipe spacing.

Figure 7.5. Front elevation of an example apartment block as a potential concrete solar collector location.

7.3 Façade typologies

Many different precast concrete façade details and aesthetics exist. A selection of these precast concrete cladding systems are described in this Section with reference to CSCs.
7.3.1 Façade integrated concrete solar collector construction details

Figure 7.6 displays two typical precast cladding details: (i) with a cavity at the back of the CSC, typical of single skin construction, and (ii) with insulation in direct contact, typical of precast concrete sandwich panel construction. The difference these two systems have, regarding the performance of a façade integrated CSC, is the contact with the insulation. These two types may be categorised as either BIST (Building Integrated Solar Thermal) or BAST (Building Attached Solar Thermal), with the efficiency of the former outperforming the latter (O’Hegarty et al., 2016). The precast concrete sandwich panel configuration (i.e. the panel insulated at the back) is considered for further analysis in this chapter.

![Diagram of façade integrated concrete solar collector construction details]

Figure 7.6. Simplified section details for two concrete solar collector façade integration examples.

The entire precast concrete face of the individual apartments may be constructed off-site. This method would minimize any joints between the CSCs and improved quality control would be expected. Alternatively, a modular system could be installed and individual CSCs may be connected in series or parallel. An example of a modular system setup is presented in Figure 7.7. The conceptual representation of the system shows three collectors connected in series. Flexible plastic pipes would make up the connection between the individual collectors allowing for thermal expansion. Even though there would be thermal losses associated with this configuration, the connections are best located at the back of the collectors as it would be difficult to install the connections side by side. The connections could be hidden behind the interior plaster board and the tank should be at a lower elevation than the collectors if a drain back system is employed. A pump would be used to circulate the fluid when there is sufficient heat to be gained from the collectors.
Figure 7.7. Conceptual connection details for the installation of a modular system with flexible connection pipes.

7.3.2 Concrete aesthetics

A selection of different coloured concrete facades are presented in Figure 7.8. The results in this chapter are documented for a dark black pigmented CSC, the aesthetic of which would be similar to the “black concrete” displayed in Figure 7.8. The aesthetics of plain, yellow and red coloured concrete cladding is also presented in Figure 7.8. The results from chapter 6 showed that the colour of the CSC has an important impact on the performance with the dark coloured CSCs outperforming the lighter coloured ones.
7.4 Energy savings

An apartment block constructed of precast concrete sandwich panels (Section 7.3) and a simple preheating system (System (iv) from Section 7.1) is considered in the following sections for analysis. The energy savings are estimated using the detailed 3D model described in Chapter 5 for a practically optimized CSC based on findings from Chapters 4, 5 and 6.
7.4.1 Practically optimized concrete solar collector

The collector considered for simulation analysis in this section is based on a practically optimised collector. Changes made to the collector may not result in an increased performance but instead are made to represent the most likely and realistic CSC. Given the available opaque area of a precast concrete clad apartment block a 2 m$^2$ CSC was considered in place of the experimentally investigated 1 m$^2$ CSC. 100 mm spaced pipes are considered so that the pipe length remained unchanged for the increased surface area and so that PEX pipes could also be used. PEX was chosen as the small improvement in performance as a result of using copper pipe did not justify its inclusion over the durably superior PEX piping. The concrete was darkened with black pigmentation. Because the precast concrete sandwich panel cladding arrangement was assumed (Section (ii) from Figure 7.6) an additional 100 mm layer of concrete was added behind the insulation to better represent this case. All other physical parameters were kept as they were in the experimental set-up (Chapter 4). A graphical summary of the changes made for this practically optimised CSC, compared with the experimental set-up, are shown in Figure 7.9.

Changes made for optimized CSC
- Black paint ($\alpha = 0.94$) $\Rightarrow$ Black pigmentation ($\alpha = 0.04$)
- Surface area 1 m$^2$ $\Rightarrow$ 2 m$^2$
- 2 wythes (as in experiment: Concrete - Insulation) $\Rightarrow$ 3 wythes (as per precast concrete sandwich panel: Concrete – Insulation – concrete)
- Pipe spacing 50 mm $\Rightarrow$ 100 mm
- No change to pipe length or any other parameter

Figure 7.9. Changes made to CSC model for analysis in this chapter (Chapter 7).

The initial tank temperature was set to the mains water temperature for that day which was assumed equal to the average daily ambient temperature for the month. The average daily solar irradiance profile for a given month and the average daily outside temperature was taken from the Photovoltaic Geographical Information System (PVGIS, 2017). A constant wind speed of 1.5 m/s was assumed (average value from reference six days in the experimental study, Chapter 4). The interior temperature was set to 20 °C. The results were investigated in relation to the Solar Fraction (SF) and the energy
output, $Q_{u,sys}$, and time dependent plots of the tank temperature and outlet temperature are also presented. The indoor wall temperature was also recorded for each climate and season.

7.4.2 European climates

The energy potential and associated economic viability of the optimized $2 \text{ m}^2$, south facing, façade integrated CSC installed on a single bedroom apartment building is simulated for four seasons in Dublin as well as three additional European climates; namely, a more northern European climate (Helsinki) and two more southern European climates, one eastern European (Sofia), and one Mediterranean (Seville). Helsinki and Sofia were chosen because precast concrete is a popular cladding material in each of these locations. According to Bennett (2005) precast concrete accounts for approximately one third of the cladding market in Finland. Bulgaria, is also well known for its concrete facades, as is portrayed in the images of apartment blocks in Sofia in Figure 7.10.

![Figure 7.10. Examples of concrete clad apartment blocks in Sofia, Bulgaria.](image)

Seville was chosen as it is representative of Mediterranean European climate, a climate with large amounts of solar radiation. The average yearly solar radiation on a south facing vertical surface is
presented in Figure 7.11, highlighting Seville, and other similar Mediterranean climates, as the highest receivers of solar radiation in Europe.

![Colour coded map of Europe as a function of the amount of solar radiation incident on a south facing vertical surface per year, including locations of the four cities assessed in this study. The graph is taken and adapted from PVGIS (2016).](image)

**Figure 7.11.** Colour coded map of Europe as a function of the amount of solar radiation incident on a south facing vertical surface per year, including locations of the four cities assessed in this study. The graph is taken and adapted from PVGIS (2016).

### 7.4.3 Results

The daily tank temperature, outlet temperature, interior wall temperature and solar irradiance profiles for each season of the four different European climates are displayed in Figure 7.12. It is assumed that the tank temperature is initially set to the mains water temperature. The starting tank temperature was therefore set equal to the average monthly ambient temperature which is different for each season and location. Maximum solar irradiances are greatest in Seville for winter, spring and autumn months, while Helsinki experiences highest solar irradiance in the summer when comparing all four locations.

According to the simulated results, the average solar fraction for the described simulated system in Dublin for the year is equal to 24.3%. The average SF ranges from 29.7% in Autumn to 14.7% in winter. The average daily efficiency was greatest in spring which is attributed to the high solar radiation and
Figure 7.12. The average simulated performance of a 2m² black pigmented concrete solar collector for each of the four seasons in Dublin, Helsinki, Sofia and Seville.
lower mains water temperatures. On average the tank temperature is expected to be at its lowest in winter and highest in autumn or spring months. No significant influence on the inside wall temperature was observed for any of the four seasons in Dublin.

The average daily SF over a year in Helsinki is 20% and seasonal changes in the performance for Helsinki were considerably greater than the other three locations. The average SF on a summer day in Helsinki is 30.5% (higher than both Dublin and Sofia) but drops to less than 5% on the average winter day. This is apparent when examining the solar irradiance profiles in Figure 7.12, with little to no radiation available in the winter seasons.

An average daily SF of 30% would be achieved by installing this CSC system on a south facing façade in Sofia. The greatest SF of 42.6% was found for an average month in autumn. While the lowest solar percentage of 18% was recorded for winter. As with both Dublin and Helsinki, no significant difference was found between the interior wall temperature and set air temperature.

This CSC would provide for more than half of an apartment’s hot water requirements if located in a Mediterranean climate, such as Seville (SF = 51%). Seville exhibits the highest SF when compared with the other three locations. However, interestingly it is Helsinki that exhibits the greatest energy output in summer; this is because of the vertical orientation of the CSCs as well as the lower mains water temperature in Helsinki compared with Seville. On an average autumn day in Seville the SF reached 73.5%, while it is, on average, lowest in the summer. This is because of the lower latitude and vertical orientation of the CSC set-up. The results are summarised in Table 7.2.

<table>
<thead>
<tr>
<th>Location</th>
<th>SF (Annual solar fraction)</th>
<th>Q_{\text{sys}} (Annual energy savings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helsinki</td>
<td>20%</td>
<td>163 kWh</td>
</tr>
<tr>
<td>Dublin</td>
<td>25%</td>
<td>187 kWh</td>
</tr>
<tr>
<td>Sofia</td>
<td>29%</td>
<td>207 kWh</td>
</tr>
<tr>
<td>Seville</td>
<td>51%</td>
<td>258 kWh</td>
</tr>
</tbody>
</table>

It is evident from Table 7.2 that installing a CSC in a more southern European climate generally results in a greater energy output. CSCs installed in Mediterranean climates offer particularly valuable energy savings with more than half of the annual energy demand for hot water supplied by the CSCs in Seville as an example. These energy savings are used to calculate the payback period of the CSC in the subsequent sections.
Annual energy savings (per complex) of 16.5 MWh/year for Helsinki, 19 MWh/year for Dublin, 21 MWh/year for Sofia and 26.5 MWh/year for Seville would be achieved by installing a 2 m² area of CSCs on the south facing façade of each block of the entire apartment building assessed in Section 7.2 (total of 102 individual apartment blocks). This is promising but the savings in auxiliary fuel need to be compared with the capital cost of installing these CSCs in order to realise their economic potential of these CSCs.

7.5 Economic analysis

Before the payback period can be realised, the cost of the CSC system needs to be determined by summing the costs of the individual system components. One of the primary advantages of CSCs is the availability, and subsequent lower cost of concrete as an absorber material, particularly when compared with standard metallic collectors. Also, a casing is not required as the concrete absorber provides the structural function of a casing system.

7.5.1 System cost

A breakdown of the system costs is first presented. The experimental costs of the CSC is based on the best price on the Irish market for 2017 for the discrete quantities of the relevant constituents (Ballylusk Quarry, 2017; Brooks, 2017; Build4Less, 2017; McMahon, 2017; MorrisDIY, 2017). The suppliers of the various materials are listed in the relevant tables. Because prices vary regularly the date of access is supplied in the reference. For bulk prices, Irish suppliers are used to get a quote if possible; in the event that a quote is not available from an Irish supplier for the bulk materials a price is taken from an online source (Alibaba, 2017). The cost of the individual concrete constituents are presented in Table 7.3.
Table 7.3. Concrete constituent costs and associated source.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost per kg</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bespoke</td>
<td>Bulk</td>
</tr>
<tr>
<td>Cement</td>
<td>€0.20</td>
<td>€0.07</td>
</tr>
<tr>
<td>Bespoke</td>
<td>build4less.ie</td>
<td>Alibaba</td>
</tr>
<tr>
<td>Sand</td>
<td>€0.11</td>
<td>€0.05</td>
</tr>
<tr>
<td>Bulk</td>
<td>build4less.ie</td>
<td>build4less.ie</td>
</tr>
<tr>
<td>10mm Limestone</td>
<td>€0.10</td>
<td>€0.06</td>
</tr>
<tr>
<td>Bulk</td>
<td>Brooksgroup.ie</td>
<td>Brooksgroup.ie</td>
</tr>
<tr>
<td>10mm Quartzite</td>
<td>€0.20</td>
<td>€0.06</td>
</tr>
<tr>
<td>Steel</td>
<td>€0.92</td>
<td>Recycled</td>
</tr>
<tr>
<td>Metal</td>
<td>Recycled</td>
<td>Recycled</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>€1.33</td>
<td>mcmahon.ie</td>
</tr>
<tr>
<td>Black paint</td>
<td>€7.30</td>
<td>€2.64</td>
</tr>
<tr>
<td>Black pigment</td>
<td>€9.15</td>
<td>€0.90</td>
</tr>
<tr>
<td>Brown pigment</td>
<td>€10.50</td>
<td>€0.90</td>
</tr>
<tr>
<td>Red pigment</td>
<td>€10.50</td>
<td>€0.90</td>
</tr>
<tr>
<td>Yellow pigment</td>
<td>€13.51</td>
<td>€0.90</td>
</tr>
</tbody>
</table>

Copper pipe is more conductive but showed minimal increase in performance as a result given the small volume of pipe compared with the surrounding concrete (as outlined in Chapter 5 and 6). Copper can, however, be spaced closer together by using welding techniques if the surface area is limited. The advantage of being able to space the pipes closer together was the reason copper was used in the experimental set-up. However, in façade integration applications, a limitation on the surface area is unlikely, as reported in Section 7.2, and, in general, PEX should be used as it is cheaper than copper and is also more durable.
Table 7.4. Pipe cost per unit length (m)

<table>
<thead>
<tr>
<th>Pipe diameter</th>
<th>Copper pipe</th>
<th>PEX pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>price per m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bespoke</td>
<td>Bulk</td>
</tr>
<tr>
<td>4 mm</td>
<td>€3.57</td>
<td>gasproducts.ie</td>
</tr>
<tr>
<td>8 mm</td>
<td>€2.15</td>
<td>screwfix.ie</td>
</tr>
<tr>
<td>10 mm</td>
<td>€2.65</td>
<td>€1.90</td>
</tr>
<tr>
<td>15 mm</td>
<td>€3.45</td>
<td>€3.01</td>
</tr>
<tr>
<td>20 mm</td>
<td>€6.18</td>
<td>€5.82</td>
</tr>
<tr>
<td>25 mm</td>
<td>€6.91</td>
<td>€5.61</td>
</tr>
</tbody>
</table>

The insulation used in this study, and in most precast concrete facades, is expanded polystyrene foam board insulation (XPS). A bespoke cost of approximately €278 per m$^3$ (Build4Less, 2017) and bulk cost of approximately €83.33 per m$^3$ (Alibaba, 2017) were assumed in this study. The storage tank with a built-in immersion heater, used in the experimental investigation, and purchased from Dublin Providers Ltd. (DPL, 2017) cost €145. The cost of the connecting hose pipe was €26 and the cost of the pump was €48. A breakdown of the capital cost of the 1m$^2$ experimental set-up and the 2m$^2$ optimised CSC (Section 7.3) is provided in Table 7.5.

In addition to the capital costs of the up-scaled experimentally constructed system, Cexp, the capital cost of four additional cases were also considered. Because a preheating system is considered in this study, a storage tank would already be in place and so the cost of the tank is not considered for the additional four cases; listed in Table 7.6.
Table 7.5. Breakdown of the capital cost of the experimental set-up, $C_{\text{exp}}$.

<table>
<thead>
<tr>
<th>Component</th>
<th>Individual item description</th>
<th>Quantity</th>
<th>Total cost (1m²) exact experiment</th>
<th>Total cost (2m²) Up-scaled for this Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete absorber</td>
<td>CEM II/A-L cement</td>
<td>40 kg</td>
<td>€8.11</td>
<td>€16.22</td>
</tr>
<tr>
<td></td>
<td>Black iron-oxide pigmentation</td>
<td>2 kg</td>
<td></td>
<td>€1.48</td>
</tr>
<tr>
<td></td>
<td>Black outdoor wall paint</td>
<td>0.16 L</td>
<td>€1.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10mm quartzite aggregate</td>
<td>97 kg</td>
<td>€19.37</td>
<td>€38.74</td>
</tr>
<tr>
<td></td>
<td>Builders Sand</td>
<td>52 kg</td>
<td>€5.86</td>
<td>€11.72</td>
</tr>
<tr>
<td>Copper piping</td>
<td>15 mm copper pipe lengths</td>
<td>18 m</td>
<td>€61.26</td>
<td>€61.26</td>
</tr>
<tr>
<td></td>
<td>Copper elbows</td>
<td>60 units</td>
<td>€18.60</td>
<td>€18.60</td>
</tr>
<tr>
<td>Storage tank</td>
<td>Insulated 100 L copper cylinder with built in immersion heater</td>
<td>1 unit</td>
<td>€145.00</td>
<td>€145.00</td>
</tr>
<tr>
<td>Connection pipes</td>
<td>Plastic hose pipe</td>
<td>30 m</td>
<td>€26.00</td>
<td>€26.00</td>
</tr>
<tr>
<td>Circulation pump</td>
<td>DAB three-switch circulation pump</td>
<td>1 unit</td>
<td>€48.40</td>
<td>€48.40</td>
</tr>
<tr>
<td>Insulation</td>
<td>XPS Insulation foam board</td>
<td>0.11 m³</td>
<td>€30.03</td>
<td>€60.06</td>
</tr>
<tr>
<td>Overall cost</td>
<td></td>
<td></td>
<td>€363.84</td>
<td>€427.51</td>
</tr>
</tbody>
</table>

The copper pipe was assumed to be replaced by PEX piping which significantly reduces the cost, without any significant change in the energy output. The additional four cases are presented in Table 7.6. $C_{\text{exp}}$ represents the cost of the one-off experimental setup and is expected to be significantly greater than either of the other four cases.

Table 7.6. Capital cost for four different cost cases.

<table>
<thead>
<tr>
<th></th>
<th>Bespoke material costs</th>
<th>Bulk material costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-Alone</td>
<td>$C_{\text{SA, bespoke}} = €221.96$</td>
<td>$C_{\text{SA, bulk}} = €131.68$</td>
</tr>
<tr>
<td>Building-Integrated</td>
<td>$C_{\text{BI, bespoke}} = €95.23$</td>
<td>$C_{\text{BI, bulk}} = €66.05$</td>
</tr>
</tbody>
</table>

Both bespoke and bulk material costs were considered, with the latter costs better representing the real costs found in the precast concrete industry. Additionally, both stand-alone and building integrated scenarios are economically investigated; for the building integrated case the costs of the concrete and insulation were not considered in the capital cost as these components are already part of the facade. This building integrated bulk materials case provides the most optimistic capital cost, $C_{\text{BI, bulk}}$, achieved by offsetting all materials and components that would be installed in the building anyway.
The costs presented in Table 7.7 only include the cost of the materials themselves. Due to the building integrated nature of the CSC system an exact estimate of other costs is not feasible. A rule of thumb adopting the standard for UK solar thermal systems is used instead where the total cost of a system is broken down into 1/3 for component parts, 1/3 for installation and 1/3 for gross profit (nett profit, product marketing, company growth and investment, research and product development) (Smyth et al., 2004). The system costs are upgraded to include these additional costs in Table 7.7.

Table 7.7. Capital cost for four different cost cases including installation and gross profit estimates.

<table>
<thead>
<tr>
<th></th>
<th>Bespoke material costs</th>
<th>Bulk material costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-Alone</td>
<td>( C_{SA,\text{bespoke}} = €665.89 )</td>
<td>( C_{SA,\text{bulk}} = €395.05 )</td>
</tr>
<tr>
<td>Building-Integrated</td>
<td>( C_{BI,\text{bespoke}} = €285.70 )</td>
<td>( C_{BI,\text{bulk}} = €198.14 )</td>
</tr>
</tbody>
</table>

7.5.2 Fuel type

The yearly economic savings are dependent on the auxiliary fuel which is being replaced. The system assessed in this study is best matched with an electric heater to top up the preheated water so special attention will be given to the savings made in terms of electricity. However, other fuels used for hot water preparation are popular in many countries. Natural gas is a popular heating fuel choice in each of the four European climates and is therefore also considered for economic analysis.

Electricity prices for the European countries considered are taken from Eurostat (2016). A 100% conversion efficiency from electricity to heat is assumed for the auxiliary heater (Oughton & Wilson, 2015). For natural gas fired boilers conversion efficiencies vary depending on the boiler technology, a conversion efficiency of 70% is assumed in this study (Oughton & Wilson, 2015). The unit cost of the fuels are presented in Table 7.8.

Table 7.8. Cost of auxiliary heating source [€/kWh]. All costs taken from Eurostat (2016) except for the cost of natural gas in Helsinki where the cost was taken from (Statistics Finland, 2017)\(^1\)

<table>
<thead>
<tr>
<th>Location</th>
<th>Fuel type</th>
<th>Electricity</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helsinki</td>
<td></td>
<td>0.153</td>
<td>0.045(^1)</td>
</tr>
<tr>
<td>Dublin</td>
<td></td>
<td>0.245</td>
<td>0.072</td>
</tr>
<tr>
<td>Sofia</td>
<td></td>
<td>0.096</td>
<td>0.039</td>
</tr>
<tr>
<td>Seville</td>
<td></td>
<td>0.237</td>
<td>0.093</td>
</tr>
</tbody>
</table>
7.5.3 Payback period

Both the simple payback and undiscounted payback period are used in this study to calculate the time it takes for the savings in replacing an auxiliary fuel to become greater than the initial investment.

7.5.3.1 Simple payback period

The simple payback period (in number of years) is calculated according to Eq. (7.1).

\[ SPp = \frac{C_{sys}}{S} \]

where the capital cost of the system, \( C_{sys} \), is documented in Table 7.8 for each case considered. \( S \) is the annual revenue savings, which is calculated according to Eq. (7.2).

\[ S = \frac{Q_{u,sys} \times C_{aux}}{\eta_{aux}} \]

where \( C_{aux} \), is the cost of auxiliary fuel and \( \eta_{aux} \) is the efficiency of the auxiliary heating system. The savings depend on the cost of energy at the given location, the annual energy savings as well as the conversion efficiency for the given fuel. The results are calculated and summarized in Table 7.9.

The life expectancy of Under Floor Heating (UFH) that uses PEX piping is often specified over 50 years. The lifetime of a CSC is assumed here to have a similar lifetime of UFH. Most evaluated payback periods are lower than the life expectancy of the CSC. Economically these may be acceptable, but, waiting over 20 years for the yearly cash flows to become positive is a significant period of time.

Payback periods for CSC installations in Seville present the best results, with payback periods ranging from 3 years (for a building integrated CSC with bulk material costs replacing electricity as the auxiliary heating source) to 37 years (for an experimental priced CSC replacing a natural gas as the auxiliary fuel). For the other three climates, the greatest energy savings are made from installing the CSC in a southern European climate like Sofia, however it is Dublin that shows the best payback periods because of the high-energy costs in Ireland. Particularly desirable payback periods were calculated when the material and system costs that would be part of the building anyway were offset from the cost. In Dublin, the payback for such a setup can be less then 5 years. These preliminary results are promising for façade integrated concrete solar collectors.
Table 7.9. Simple payback, $SP_p$, in number of years, for the building integrated and stand-alone CSC systems for four European countries.

<table>
<thead>
<tr>
<th>Location: →</th>
<th>Helsinki</th>
<th>Dublin</th>
<th>Sofia</th>
<th>Seville</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy savings(kWh/year):</td>
<td>163</td>
<td>187</td>
<td>207</td>
<td>258</td>
</tr>
<tr>
<td>Replacing Electricity (€/kWh):</td>
<td>0.153</td>
<td>0.245</td>
<td>0.096</td>
<td>0.237</td>
</tr>
<tr>
<td>Standalone Bespoke, $C_{SAB}$: €666</td>
<td>26.7 years</td>
<td>14.5 years</td>
<td>33.5 years</td>
<td>10.9 years</td>
</tr>
<tr>
<td>Standalone Bulk, $C_{SAB}$: €395</td>
<td>15.8 years</td>
<td>8.6 years</td>
<td>19.9 years</td>
<td>6.5 years</td>
</tr>
<tr>
<td>Building integrated Bespoke, $C_{IB}$: €286</td>
<td>11.5 years</td>
<td>6.2 years</td>
<td>14.4 years</td>
<td>4.7 years</td>
</tr>
<tr>
<td>Building integrated Bulk, $C_{IB}$: €198</td>
<td>7.9 years</td>
<td>4.3 years</td>
<td>10 years</td>
<td>3.2 years</td>
</tr>
<tr>
<td>Experiment, $C_{exp}$ : €1,283</td>
<td>51.4 years</td>
<td>28 years</td>
<td>64.5 years</td>
<td>21 years</td>
</tr>
<tr>
<td>Replacing Natural gas (€/kWh):</td>
<td>0.045</td>
<td>0.072</td>
<td>0.039</td>
<td>0.093</td>
</tr>
<tr>
<td>Standalone Bespoke, $C_{SAB}$: €666</td>
<td>63.5 years</td>
<td>34.6 years</td>
<td>57.7 years</td>
<td>19.4 years</td>
</tr>
<tr>
<td>Standalone Bulk, $C_{SAB}$: €395</td>
<td>37.7 years</td>
<td>20.5 years</td>
<td>34.3 years</td>
<td>11.5 years</td>
</tr>
<tr>
<td>Building integrated Bespoke, $C_{IB}$: €286</td>
<td>27.3 years</td>
<td>14.9 years</td>
<td>24.8 years</td>
<td>8.3 years</td>
</tr>
<tr>
<td>Building integrated Bulk, $C_{IB}$: €198</td>
<td>18.9 years</td>
<td>10.3 years</td>
<td>17.2 years</td>
<td>5.8 years</td>
</tr>
<tr>
<td>Experiment, $C_{exp}$ : €1,283</td>
<td>122.4 years</td>
<td>66.7 years</td>
<td>111.2 years</td>
<td>37.4 years</td>
</tr>
</tbody>
</table>

7.5.3.2 Undiscounted payback time

The simple payback method, which simply calculates the time needed for annual cash flows to become positive, does not include the inflation rate of the fuel cost, $i_f$. To account for the inflation rate, the undiscounted payback method is used. This is the most common method used when economically analysing solar thermal energy systems according to Duffie & Beckman (2013). It is now widely accepted that the cost of energy is set to rise, but the precise inflation rate is difficult to predict. This study follows Gill et al. (2016) in assuming a 3% inflation rate. The payback period, $P_p$, using this method is calculated according to Equation Eq. (7.3).

$$P_p = \frac{\ln[c_{exp}(1+i_f)+1]}{\ln[i_f+1]}$$  

Eq. (7.3)

The payback periods, $P_p$, using this method are documented in Table 7.10.
Including the inflation rate in the economic analysis shows favourable results when compared with the simple payback method. It is evident from this Table that, unlike the energy output, a trend of improved payback periods in countries with a more southerly location is not necessarily true. This is attributed to the large variations in energy and fuel costs across Europe. While Seville still performs the best (providing the shortest payback periods), Sofia is outperformed by Dublin due to the higher cost of fuel in Dublin. In fact, the cost of electricity is so cheap in Sofia that CSCs in Helsinki would provide shorter payback periods when replacing electricity as the auxiliary source.
Chapter 8

Conclusions and Recommendations
8 Conclusions and Recommendations

Precast concrete cladding commands a considerable share of the façade cladding market (e.g. ≈ 33% in Finland (Bennett, 2005)). Enhancing its functionality as a building integrated renewable energy source can augment its merits and further its applicability. This research has shown that Concrete Solar Collectors (CSCs) have the potential to be a viable renewable energy technology, when integrated in the building’s facade. They have been shown to produce approximately one quarter of the domestic hot water demand in middle to Northern Latitude European climates and almost half of the same hot water demand in Mediterranean climates. However, there is a paucity of research in the field of CSCs, particularly for façade integration. This was realised following an in-depth review of the Building Integrated Solar Thermal (BIST) literature as presented in this thesis (Chapter 2).

Precast concrete cladding already exhibits a range of advantages over other cladding technologies, including greater durability, inherent fire resistance and advantageous thermal qualities. Also, considering the extensive variety of surface finishes, textures and colours available with contemporary concrete, CSCs allow for a wider range of aesthetical finishes than both metal and polymer absorber based solar thermal collectors. This is particularly pertinent when designing for façade integration. CSCs are also relatively simple to construct in comparison to other more complex collectors. A novel, low-cost experimental set-up of a CSC was successfully designed, fabricated and installed in Dublin, a good example of a middle to Northern Latitude European climate (Chapter 3).

Material investigations, undertaken during this research study, have shown thermal conductivity and surface absorptance to be two of the most important performance parameters. Increasing the absorptance by applying dark colours such as red, brown and black was shown to improve the performance of the concrete solar collectors considerably. Aggregate replacements and mix additives have been incorporated to improve the thermal conductivity of concrete which is shown to improve the performance of the concrete solar collector; for example, by replacing limestone aggregate with the more conductive quartzite aggregate the daily efficiency of the CSC has been shown to improve by approximately 2% on a clear day. Incorporating a high dosage of steel fibres in the concrete mixture also increases the overall conductivity of the mixture, but the slight improvement in performance should be weighed against the additional cost and lower workability of the concrete mixture. For small performance improvements replacements or additions in the concrete make-up are practically justified only if the alternatives are matched on price and availability. The thermal conductivity of concrete was found to be appropriate to achieve daily efficiencies similar to that of metallic absorber based unglazed collectors and greater than that of polymer absorber based unglazed collectors.

Concrete solar collectors are an alternative to these standard metallic or polymer based unglazed solar collectors, which can be seamlessly integrated into the façade of buildings as a precast concrete cladding
element. Through simulation methods (Chapter 5 and 6), CSCs have been shown to provide for a significant proportion of the hot water energy demand of single bedroom apartment blocks in four different European climates (20% in Helsinki, 25% in Dublin, 29% in Sofia and 51% in Seville). Economically CSCs also make sense due to their low pay back periods (10 years in Helsinki, 5.8 years in Dublin, 12.1 years in Sofia and 4.4 years in Seville for a bespoke building integrated system replacing electricity as the auxiliary energy source) and the fact concrete has superior durability properties to the typical metallic based solar absorbers.

Although the applications of concrete solar collectors are limited by their low output water temperature when compared with flat plate or evacuated tube collectors, they are a viable technology for low temperature applications (e.g. swimming pools) or for water preheating, where they have the potential to offer considerable energy savings to buildings. A summary of the key findings of this research project, the contribution to knowledge which meet the objectives outlined in Chapter 1, and the future research possibilities are outlined in the subsequent sections that conclude this thesis.

8.1 Key findings
A novel experimental and numerical investigation is presented in this thesis. The key findings of the experimental work are first listed.

- Approximately one quarter of the hot water energy demand of a single occupant dwelling can be provided by CSCs installed on a south facing facade in Dublin (Ireland).
- Useful thermal energy can be harvested by vertical façade collectors on clear days in winter months, a conclusion that holds for all façade integrated solar collectors.
- Peak daily energy outputs are observed in spring and autumn, but, on average, summer months exhibit the greatest daily energy output.
- A daily 100% solar fraction was not observed for any single day of any of the four seasons in Dublin. This is due to the unglazed nature of the CSC and its subsequent inability to reach application temperatures greater than 50 °C. A CSC must therefore be used with an auxiliary heating source.
- 3.2 kWh of thermal energy is extracted per kWh of electric energy used by the pump for 1% efficiency pump and 18.3 kWh a the 10% efficiency pump over a 6 day period that includes 3 clear days, a partly cloudy day and 2 cloudy days.

To further assess the potential energy output of CSC systems in different climates a 3D numerical model was developed. The key findings are as follows.
The verified and validated CSC model showed annual energy outputs of between 160 kWh/year for Northern European climates and 260 kWh/year for Southern European climates. A correlation between the annual energy output and the proximity to the equator was observed for the four European climates that were studied (Helsinki = 163 kWh/year; Dublin = 187 kWh/year; Sofia = 207 kWh/year; Seville = 258 kWh/year).

Solar fractions of 20% (for Helsinki), 25% (for Dublin), 29% (for Sofia) and 51% (for Seville) were estimated using the novel 3D model. Results from the model and experimental studies were in agreement, for example, each showing that approximately one quarter of the hot water demand of a small dwelling in Dublin could be provided by a façade integrated CSC.

Seville displayed, by far, the greatest annual average solar fraction of the four assessed climates. This is because of the greatest energy output but also because of the higher mains water temperature and hence lower requirement of thermal energy.

The 3D model estimated a solar fractions as high as 38% for a clear day in Spring in Dublin (25th of March 2017).

The model predicted that if an antifreeze of 50% glycol 50% water was employed on this day the SF would reduce from 38% to 31% due to the inferior thermal properties of the glycol water mixture. It is proposed that a well-designed drain back system would instead offer a more economic freeze protection.

The findings of a further in-depth, parametric investigation of CSCs, using a simplified 2D model for computational efficiency, are presented below.

The daily efficiency of an optimally tilted CSC increases from $\eta_d = 42\%$ to $\eta_d = 56\%$ on a clear summer day by replacing the standard limestone aggregate with quartzite aggregate and painting the surface black. Neither of these two alterations to the CSC resulted in significant additional costs.

The daily efficiency of a CSC, can further increase from $\eta_d = 56\%$ to $\eta_d = 72\%$ on a clear summer day by improving the material (increased thermal conductivity) and surface properties (increased solar absorptance, reduced thermal emittance) of the concrete, within the range of values found in the concrete solar collector literature.

The daily efficiency can be increased further from $\eta_d = 72\%$ to $\eta_d = 76\%$ by optimising the concrete solar collector geometry within the range of values found in the concrete solar collector literature (exposing the pipes closer to the surface, increasing pipe diameter and reducing pipe spacing).
• It should be noted however that the geometric and material improvements are based on a combination of values recorded in the literature that are not always practically achievable or cost effective.

The economic potential of the CSC was assessed for different climates. The main conclusions are as follows:

• The cost of a CSC was estimated to cost between €198 – €1,283 to construct depending on whether the CSC is integrated as part of the system and façade, and whether bulk materials are used.

• Considering the cost of the experimental system set-up in Dublin, the payback period was estimated to be 20.6 years if replacing electricity and 37.2 years if replacing natural gas.

• For a bespoke building integrated CSC system the payback periods are reduced to 5.8 years for electricity and 12.5 years for natural gas. If bulk material costs are considered the payback periods are expected to drop to approximately 4.1 years (replacing electricity) and 9.1 years (replacing natural gas).

• The optimum payback periods for Helsinki (7.2 years for electricity; 15.2 years for natural gas) and Sofia (8.9 years for electricity; 14.1 years for natural gas) are longer than Dublin.

• Optimum payback periods estimated for Seville were shorter than Dublin, with a positive return on the initial investment expected after 3.1 years when replacing electricity and 5.4 years when replacing natural gas.

8.2 Contributions to knowledge.

The aim of this research was to investigate Concrete Solar Collector (CSC) technology for facade integration and assess its ability to supply the thermal energy demand of buildings. This thesis has addressed the five core objectives outlined in the introduction of this thesis.

1) To present a comprehensive literature review of building integrated solar thermal solutions and concrete solar collectors.

A comprehensive literature review of building integrated solar thermal solutions and concrete solar collectors has been conducted. A concise review manuscript, entitled “Review and analysis of solar thermal facades”, was published in the Solar Energy journal (O’Hegarty et al., 2016).

A paucity of research on façade integrated concrete solar collectors has been identified from the current building integrated solar thermal literature. CSC related literature lacks:
(1) a rigorous assessment of individual parameters (geometric dimensions, material properties and surface properties),

(2) documented experimental results of a CSC in a European climate and,

(3) documented detailed numerical models of a CSCs and their systems.

2) To design, fabricate and install a CSC system

An experimental CSC system has been designed, fabricated and installed on the roof in Trinity College Dublin. The thermal conductivity of five different concrete mixtures and, the absorptance of eight different surface finishes have been tested. A black painted concrete with quartzite aggregate was subsequently identified as providing the optimum thermal and optical properties.

3) To experimentally investigate the performance of a CSC system.

The experimental set-up was successfully used to monitor the thermal response of a CSC throughout the four seasons of the year. For each season the daily temperature profiles were presented, for example, clear and cloudy days as well as for days with average solar irradiance for the month. Greatest temperature differences between storage tank fluid temperature and outside ambient temperature were recorded for spring months. The response of the system when changing the insulation, tank volume, flow rate and pump control was determined, noting each as having a significant influence on the performance of the system.

4) To numerically model a CSC.

Novel 3D and simplified 2D numerical models were developed and verified. Both models were validated with the experimentally measured results recorded from the experimental CSC set-up.

The 3D model was developed so it could be used as a part of simple hot water preheating systems and has subsequently been used to realise the performance of difference CSCs in different European climates. The description of the 3D numerical model as well as simulation results from the model were published in “Concrete solar collectors for façade integration: An experimental and numerical investigation” in the Applied Energy journal.

The simplified 2D model was designed so that it can provide results without significant computational effort. The quick simulation times mean that it is suitable for parametric investigations which require multiple individual simulations. A parametric investigation was subsequently conducted using this 2D model. The results of this parametric investigation were published in the Solar Energy journal in a paper entitled “Parametric investigation of concrete solar collectors for façade integration”.

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Together the 2D and 3D models, along with the experimental results, were used to identify an optimum CSC as well as a practically and economically optimum CSC.

5) To investigate the economic feasibility and applicability of CSCs.

The economic feasibility and applicability of a CSC was investigated. The building, façade and hot-water-system, best suited for CSC installations, was identified and the energy output was calculated for four different European climates. The cost of the CSC was determined as well as the extrapolated cost if bulk materials are used, and if the cost of the materials are offset from the total cost. Using the energy output for the different climates and the capital cost of the different cost cases the payback periods were calculated and presented.

8.3 Future research

The research has fulfilled the objectives outlined in Chapter 1 but the need for some other future research has become apparent. The future research is outlined under the following sub headings.

8.3.1 Investigation of design adaptation for a radiative cooling system

Radiative cooling from the surface of the concrete collector to the night sky was exploited to cool the storage tank water temperature over night by continuously circulating the water through the CSCs. There is the potential to adapt the CSCs to a hybrid DHW preheating and night time cooling system for warm climates. The potential of these CSCs as part of a preheating system in Mediterranean countries has already been highlighted in this study.

8.3.2 Investigation of structural and durability characteristics

One of the advantages of CSCs compared with other collectors is their inherent durability. The reported lifetime of solar thermal systems are typically in the region of 20 years. The reported lifetime of screed cast underfloor heating systems is almost double that. CSCs are similar in materiality and configuration to these systems. CSCs could be expected to have lifetimes well beyond the lifetime of contemporary typical solar thermal technologies. Investigation of the optimum structural configuration and the durability of CSC cladding present much scope for further research. A range of systems could be tested with different geometries and configurations, and in different environments.

8.3.3 Addition of spectrally selective coatings to enhance performance

The parametric study identified the thermal emittance of the concrete surface as one of the key performance parameters. It would be interesting to investigate different spectrally selective coatings applicable to concrete surfaces. However, this research would most likely require expensive spectrophotometers and integrated sphere set-ups in order to accurately measure wavelength specific
reflectance. The spectrally selective coating itself should also be durable and low cost, in keeping with the CSC design concept and thereby justify its inclusion.

8.3.4 Toward an explicit standard validation method

It has been documented in previous literature that there is no explicit standard for the validation of solar thermal system models. It is clear from this thesis, as well as other previous studies, that an explicit standard validation method would provide a useful tool for solar thermal model developers.

8.3.5 Investigation of sky temperature models

One of the greatest sources of error in the applied model is the effective sky temperature. It has been shown in this study that modelling the sky temperature based on empirical models of the ambient temperature alone can result in erroneous results, particularly if a range of both cloudy and clear days need to be modelled. A detailed comparative study of the available sky temperature models would provide a valuable insight to widely used, but often inaccurate (for the given application) sky temperature models, for building and energy researchers.

8.3.6 CSC model integration with complex heating system model

Both experimental and simulation results showed good energy output from the vertically orientated CSC in spring and autumn months as well as on clear days in winter. These energy outputs coincide with space heating requirements and it would be interesting to simulate these CSCs as part of a space heating system.

For modelling other complex systems, such as a space heating system with a heat pump, the FEM-CFD software (used to model the CSC) would need to be combined with an energy systems software (e.g. TRNSYS) as well as a host/server to ensure data exchange between both programs (e.g. MATLAB). This method is computationally inefficient but may be feasible for one off designs. Another possibility would be to develop an empirical model of the CSC based on the results from the detailed 3D FEM model and use this model directly in the energy systems software. Both methods offer scope for future research.

8.3.7 Full scale experimental proof of technology

The natural next step in the research of CSCs would be to install a CSC in a real building and document all energy savings as well as the capital cost and saving on fuel costs. It is expected that such a study would be timely but would be the ideal next step for the CSCs to become a marketable product - a product that can be easily constructed in a precast concrete facility. This would also be a good
opportunity to analyse any long term potentially negative effects on the collector’s performance including the degradation of the surface.
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