

LOCAL HEAT TRANSFER FROM MICRO IMPINGING JET ARRAYS

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ABSTRACT. Much research has been carried out into the area of large scale impinging jet heat transfer but smaller scale jets are relatively unexplored in comparison. In this study 620 μm diameter confined air jets impinge normally onto an ohmically heated flat surface. The resulting surface temperature distributions, from a 3 x 3 in-line jet array, are recorded with an infrared camera with a spatial resolution of 47.5 μm . The inter jet spacing was kept constant at 4 jet diameters and the jet-to-target spacing was varied from 0.42 to 3.35 jet diameters. Tests were carried out at jet Reynolds numbers of 3000 and 6300 corresponding to Mach numbers of approximately 0.21 and 0.43. Results are presented in terms of local heat transfer coefficient distribution. The results indicate that small scale jet impingement heat transfer is fundamentally different than its larger scale counterpart. The effects of entraining warm fluid into the pre-impact jet are thought to considerably affect the heat transfer behaviour of the jets.

Keywords: *microscale, jet impinging, convective heat transfer, heated thin foil method, infrared thermography*

INTRODUCTION

Impinging jet flows are capable of achieving high heat transfer due to the very thin boundary layers resulting from them. A comprehensive literature review exists for macro scale impinging jet heat transfer, Martin [1], Webb and Ma [2] and Garimella [3]. However, the potential use of jets in thermal management of electronic devices has generated an interest in micro scale jet heat transfer. Garimella and Rice [4] noted that the effect of nozzle diameter on heat transfer is not always captured by conventional Nusselt number correlations. San et al. [5] noted similar effects for jet diameters smaller than 6 mm. Pence et al. [6] noted that direct scaling of macro scale heat transfer equations, as correlated by Martin [1], to the micro scale is improper as the fluid flow is dynamically different. Moderate Reynolds number jet flows can correspond to high Mach numbers in micro scale jets since the small characteristic lengths result in high jet velocities. The goal of this study is to investigate how parameters such as Reynolds number and nozzle-to-impingement surface spacing influence the heat transfer mechanisms for multiple micro-sized jets.

EXPERIMENTAL SET-UP

This study looks at a 3 x 3 in-line jet array with 620 μm diameter orifices, as depicted in figure 1. Several geometric and flow parameters are known to affect the local heat transfer resulting from such an array. Tests were carried out at a fixed inter jet spacing of $S/D = 4$, two Reynolds numbers were tested, $Re = 3000$ and $Re = 6300$ and the nozzle-to-impingement surface spacing was varied in increments from 0.42 to 3.35 jet diameters.

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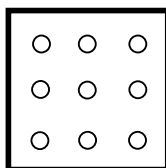


Figure 1. Test nozzle configuration for the 3 x 3 in-line array

The experimental facility used is illustrated in figure 2. The air flow to the test section was controlled with a MKS type 1179A mass flow controller ($0\text{--}20\text{ LPM} \pm 1\% \text{ F.S.}$). Air enters a plenum chamber where the stagnation temperature is monitored with a 1.5 mm diameter type-K thermocouple. The air inside the plenum then passes through a pipe nozzle with a development length, L_{dev} , of 20 jet diameters. This is sufficiently long to ensure a fully developed velocity profile at the exit of the nozzle, Incropera [7]. The nozzle surface is subject to heating from the foil beneath it. In order to maintain both the temperature of the air in the plenum and the temperature of the nozzle surface at ambient conditions, cooling channels were embedded into the nozzle plate. The coolant, water, is maintained at ambient temperature by passing it through a cross flow heat exchanger. Both the heated foil and nozzle plate had widths greater than 40 jet diameters as San et al. [5] demonstrated that stagnation Nusselt numbers varied with the width of the heated surface for $W/D < 40$. The heater assembly consisted of a 25 μm thick stainless steel foil (AISI 321 - Fe/Cr18/Ni9/Ti) which was heated ohmically by a Lambda DC power supply capable of supplying 200 A at 6V. The potential difference across the foil was measured from voltage taps attached to the foil. Construction of the impingement surface involved bonding the 80 mm by 28 mm foil to two copper bus bars with an electrically conductive, silver loaded epoxy. One bus bar was then fixed to a rigid stand whilst the other was mounted to a section of the stand which could traverse linearly along a pair of guidance rods. After the foil was cured, springs, located along the guidance rod, were adjusted to tension the foil. This tensioning system ensured that the foil remained continuously taut with varying system temperature.

The jets impinged onto the upper surface of the foil, however, as the metallic foil is so thin, calculations of the Biot number showed that the temperature drop across the thickness of the foil was negligible. Therefore, by cooling the upper surface with impinging jets it is possible to indirectly and non-intrusively record the resulting upper surface temperature distribution from the lower surface of the foil via infra red thermography. To facilitate accurate temperature measurement, the exposed underside area of the foil was covered with a thin layer of matt black paint with an emissivity $\epsilon = 0.95$. Utilizing a FLIR ThermoCam A40 fitted with a close focus lens, IR thermal images were captured to record the temperature distribution of the foil. The total camera viewing area was 15.2 mm by 11.4 mm with a spatial resolution of 47.5 μm and a frame rate up to 50 Hz. The nozzle exit to impingement surface spacing, H , was set by zeroing the system through placing the jet exit surface in contact with the impinging surface. Subsequent to zeroing a traversing stage fitted with micrometers was used to accurately position the plenum relative to the foil.

DATA REDUCTION AND EXPERIMENTAL UNCERTAINTY

As some tests were carried out at large Mach numbers, $M = 0.43$, for which compressibility effects were significant, Re and M were calculate from an iterative approach outlined by Goodro et al. [8]. Goldstein et al. [9] determined that impinging high speed jets caused non-uniform temperature profiles on the adiabatic surface. This variation in temperature was accounted for by using the adiabatic wall temperature as the reference temperature in the calculation of the local heat transfer coefficients, equation 1.

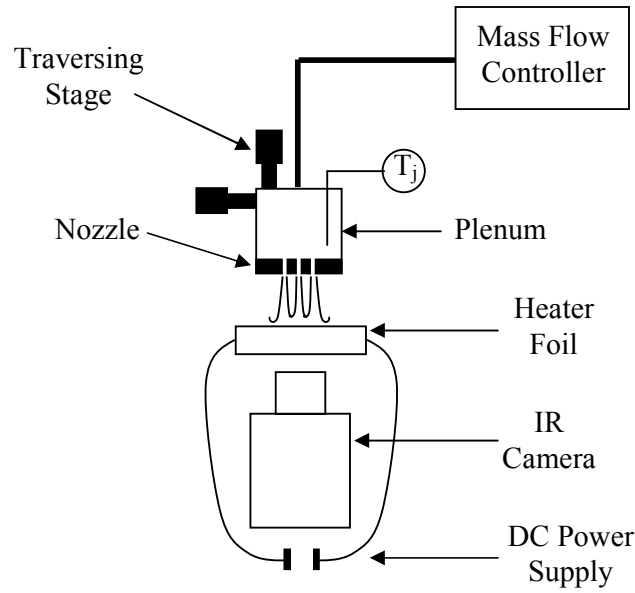


Figure 2. Experimental facility.

$$h = \frac{q''_{\text{conv, jet}}}{(T_{\text{h,w}} - T_{\text{a,w}})} \quad (1)$$

The adiabatic wall temperature, $T_{\text{a,w}}$, and the heated wall temperature, $T_{\text{h,w}}$, were obtained by recording the temperature distribution resulting from the 9 jets impinging onto first an unheated and subsequently a heated impingement surface, figure 3. The heat flux due to forced convection, $q''_{\text{conv, jet}}$, was calculated from an energy balance, equation 2.

$$q''_{\text{conv, jet}} = q''_{\text{gen}} - q''_{\text{rad}} + q''_{\text{lc}} \quad (2)$$

The largest term on the r.h.s. of equation 2 is q''_{gen} , the heat flux generated in the foil. The heat flux due to radiation, q''_{rad} , is relatively small however the heat flux due to lateral conduction, q''_{lc} , which is negligible in a macro scale system, is of the same order of magnitude as the generated heat flux. Calculating q''_{lc} required numerically approximating the 2nd spatial derivatives of heated temperature distribution. These derivatives were achieved by using finite difference approximations, however spatial fluctuations in the temperature field have a severe impact on numerical approximations of the 2nd spatial derivatives of temperature. To overcome this, a Wiener filter is used to smooth the data, Rainieri et al. [10].

In order to quantify the level of uncertainty in the lateral conduction component a Monte Carlo technique was implemented for each Reynolds number tested. For the purpose of uncertainty calculation, each measurement is denoted by x_i and the uncertainty in the measurement w_i . The result of a calculation using these measurements is denoted Z and the uncertainty in the calculated result is denoted by w_z . The uncertainty w_z is calculated from the method of Kline and McClintock [11] using the following equation:

$$w_z = \sqrt{\left(\sum_{i=1}^n \left[\frac{\partial Z}{\partial x_i} w_i \right]^2 \right)} \quad (3)$$

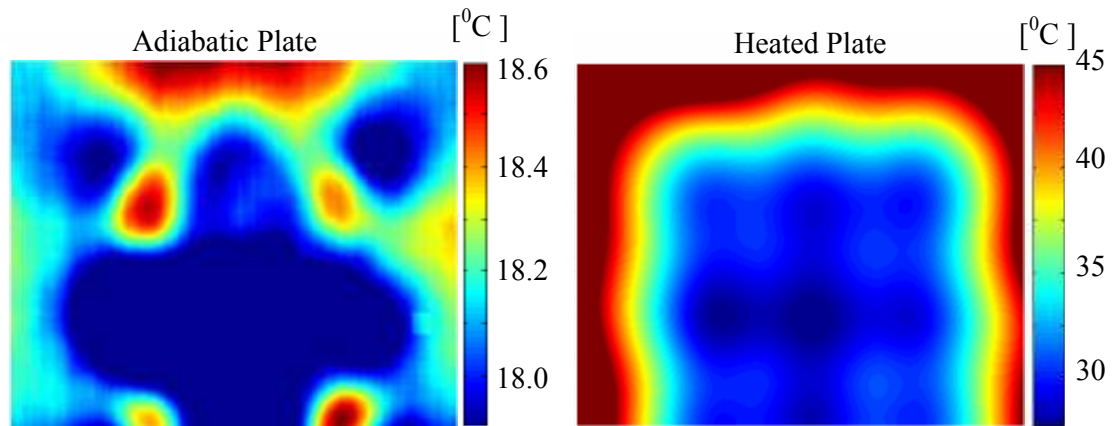


Figure 3. Temperature distributions resulting from a 3 by 3 inline jet array impinging onto a cold and a hot surface at $H/D = 2.1$ & $Re = 6300$.

The maximum experimental uncertainties are summarized in table 1.

Table 1
Calculated uncertainty

S/D (mm)	H/D (mm)	Re		q''_{lc} (W/m ²)		h (W/m ² K)	
		3000	6300	Re=3000	Re=6300	Re=3000	Re=6300
±7%	±10%	±4%	±8%	±12%	±9%	±12.5%	±9.5%

RESULTS AND DISCUSSION

Hubar and Viskanta [12] studied a 6.35 mm diameter 3 by 3 square jet array and found varying nozzle to target spacing from 1 to 6 jet diameters has little effect on the resulting Nusselt Numbers. However Garimella and Schroeder [13] later showed, for a similar shaped 1.59 mm diameter array, that decreasing nozzle to target spacing increased heat transfer. Similar results were seen for the tests carried out in this investigation, as illustrated in figure 4. Behbahani and Goldstein [14] attributed these findings to increasing turbulent intensity found at decreasing H/D values due to increased mixing caused by spent fluid from neighbouring jets. Another phenomenon that affects heat transfer and depends on nozzle to impingement spacing is entrainment. Azar et. al. [15] describes how entrainment can modify a jet's pre-impact temperature and Striegl and Diller [15] showed that the entrainment of warm air decreases with decreasing H/D .

In all test for $H/D < 3$, the central jet of a nine-jet array had considerable larger stagnation region heat transfer than its peripheral jets, figure 4, which is consistent with findings of Garimella and Schroeder [13]. This could be caused by the effects of turbulence intensity and entrainment. The central jet is surrounded by eight jets so it is expected that the temperature of the entrained fluid is lower in the central jet than in the fluid entrained by the peripheral jets. The increase in the stagnation heat transfer for the central jet compared to the peripheral jets is more pronounced at large Reynolds numbers which can be clearly seen at the bottom of figure 4.

Figure 5 shows the local heat transfer at values of $H/D = 0.42, 1.68$ & 2.94 and $Re = 3000$ & 6300 . The images show the heat transfer between the stagnation zones. The central zone between any 4 adjacent jets demonstrates local minima in heat transfer. However, the linear zones located between

2 adjacent jets demonstrated relatively high heat transfer which has been associated with inter jet interaction. The interaction zones between the centre jet and adjacent peripheral jets demonstrated higher heat transfer than the interaction zones between purely peripheral jets.

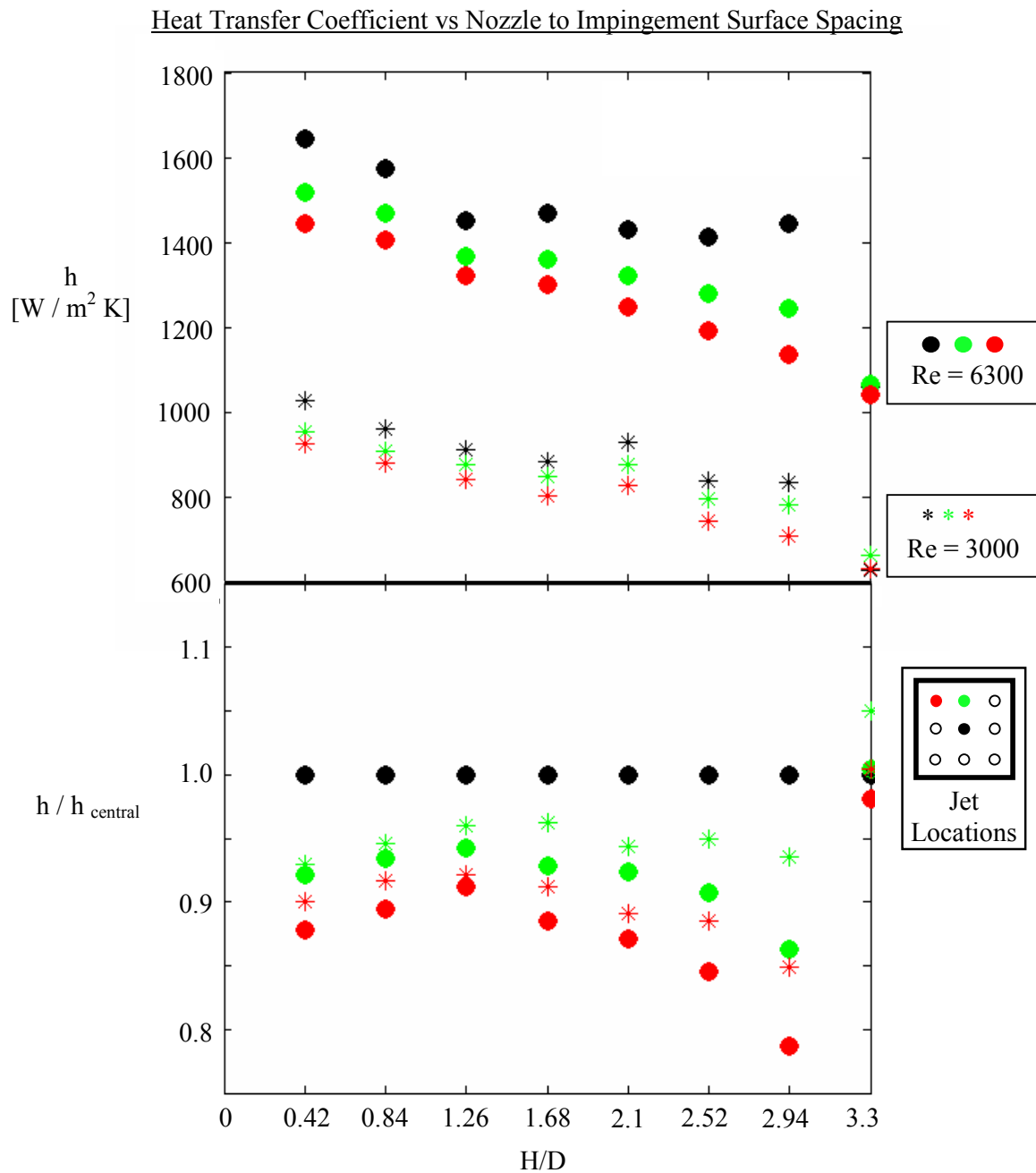


Figure 4. Stagnation point heat transfer coefficients at different nozzle to impingement surface spacings, for 3 individual jets found in a 3 x 3 inline jet array.

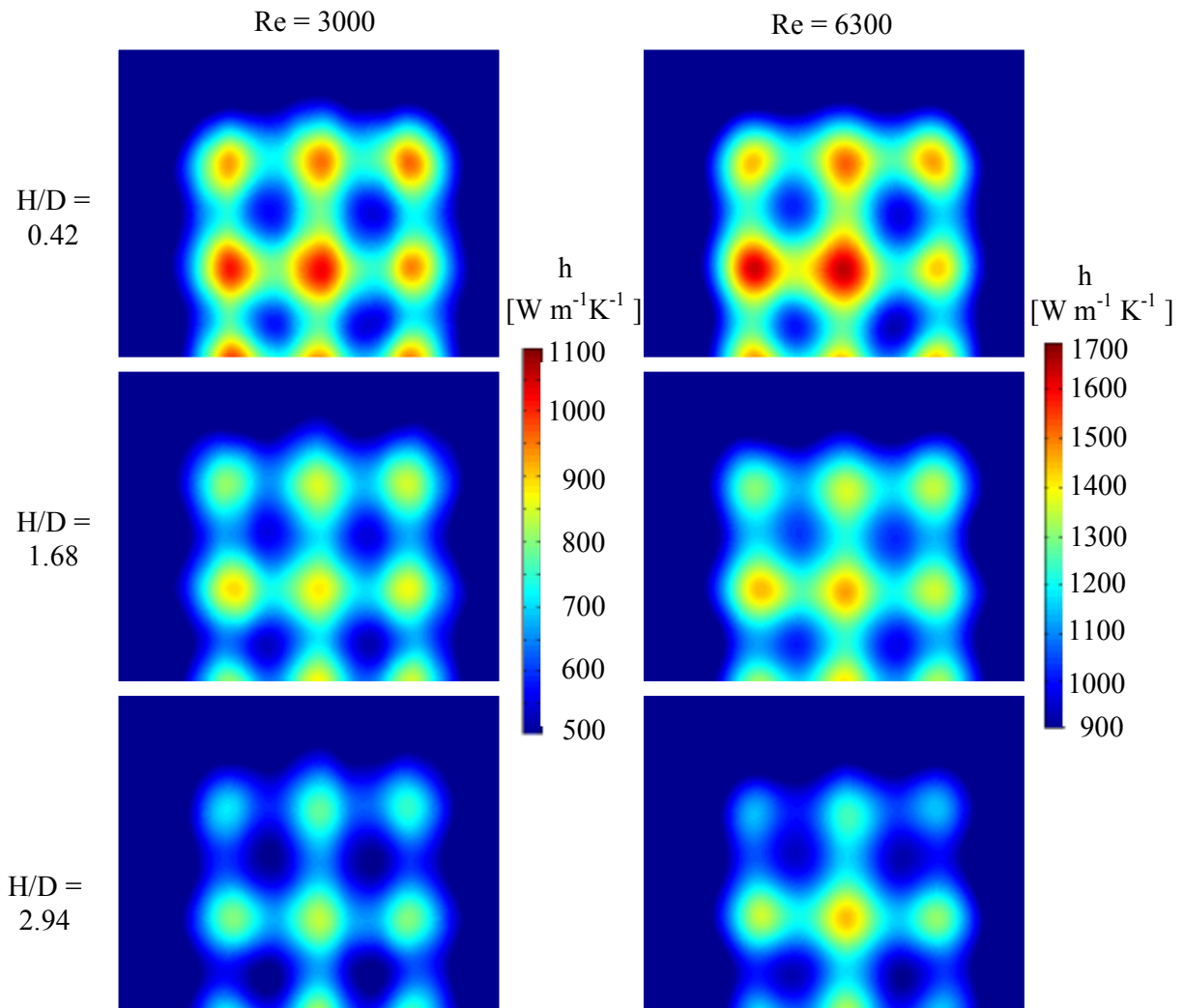


Figure 5. Local heat transfer distributions resulting from a 3 x 3 inline jet array impinging at H/D values of 0.42, 1.68 & 2.94 and at Reynolds numbers of 3000 & 6300.
Each image is 10 mm by 13 mm.

CONCLUSIONS

Micro jet heat transfer for a 3 x 3 array of 620 μm diameter jets was investigated experimentally. Experiments were performed using a heated thin foil and infrared thermography at a interjet spacing, S/D , of 4 and Reynolds number of 3000 & 6300; nozzle to impingement surface spacing was varied from 0.42 to 3.35 jet diameters.

The small length scale associated with micro jets suggests that Reynolds number scaling from the macroscale to the microscale is inappropriate, due to the high velocities associated with relatively low Reynolds numbers. These velocities result in high subsonic Mach numbers making compressibility a factor. It is thought that entrainment effects and turbulence intensity are vastly more significant at smaller scale.

The microjets studied demonstrated increasing heat transfer, both local and area averaged, with an increased Reynolds number. Heat transfer was also found to increase with decreasing nozzle to impingement surface spacings. Post-impact jet interactions lead to increased heat transfer in regions found between adjacent jets. The highest heat transfer was found to be in the stagnation zone associated with the central jet.

NOMENCLATURE

D	Jet diameter, (m)
H	Distance between the nozzle exit and the impingement plate, (m)
S	Inter jet spacing, (m)
T	Temperature, (K)
W	Width of the heated foil, (m)
q''	Heat flux, (W m^{-2})

Subscripts

a	Adiabatic
conv	Convection
dev	Development (length)
gen	Generated
h	Heated
lc	Lateral conduction
rad	Radiation
stg	Stagnation
w	Impingement surface (wall)

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