Summary of Proposed Research Program for Doctor of Philosophy

Title

Heat transfer enhancement and fluid flow characteristics associated with jet impingement cooling

Abstract

With the increasing miniaturization of Micro-Electro-Mechanical Systems (MEMS) heat dissipation is rapidly becoming a problem to further development in micro-electronics industries. Jet impingement cooling has often been identified as a method with the potential to provide the high rates of heat transfer needed for rapid heat removal. To this end an in-depth numerical study of jet impingement will be performed to quantify the heat transfer enhancement in a useful manner. The numerical study will be carried out using the commercial finite volume computational fluid dynamics software FLUENT. Experiments will be performed to verify the results obtained from simulation.

Based on an extensive review of published work in addition to preliminary studies carried out during the period of provisional candidature, the results from this research are expected to show significant benefit in using jet impingement cooling in MEMS applications. These results (both experimental and numerical) will additionally be used to develop a correlation between the heat transfer and other relevant parameters of the jet. An accurate correlation of this nature will be a significant contribution to the field as it will allow jet impingement cooling to be more effectively applied to a wider range of industrial problems.

Objectives

The proposed research programme is an in-depth study into the heat transfer enhancement available by using jet impingement. Impetus for the research is provided by the increased cooling requirements resulting from minaturisation in Micro-Electro-Mechanical Systems (MEMS) (Chu and Simons [1] provides detail of this phenomena), and therefore emphasis will be placed on small scale jets. The objectives for the research are as follows:

i) to perform a preliminary study into the mechanisms providing heat transfer improvement in jet impingement, with emphasis on identifying modifications which best enhance these mechanisms (including interrupted jets, swirling jets, spray jets amongst others which are outlined below)

ii) to perform a detailed parametric study of the heat transfer improvement due to modifications identified in part (i)

iii) to design and construct experimental apparatus suitable to verify and substantiate the results obtained from the conclusion of part (ii)

iv) to use data from parts (ii) and (iii) to develop a correlation for heat transfer in impinging jets over a number of relevant parameters

Background

With the current trend in MEMS development leading to higher and higher circuit densities heat generation within these devices is increasing at a fast rate and is rapidly becoming the limiting factor to obtaining further minaturisation. At present, research into to this problem is extremely active with a range of alternative solutions being investigated (Mudawar [2] provides a review of such emerging technologies). The impinging jet is one possible solution to the problem with the improvement in heat transfer well reported in the literature (see [3–6]). Due to this wide recognition as a potentially effective solution, jet impingement cooling will be the subject of the proposed research. In keeping with the desired application to MEMS the research will place emphasis on small scale jets.

Current research in the field is predominantly aimed at improving the heat transfer rates by various modifications to the standard jet. As these modifications will form a significant part of the research a brief review of the recent literature is desirable and has been included below. The review is divided into two categories, the first dealing with experimental investigations and the second with numerical and theoretical investigations.

Experimental Investigations

Numerous experimental studies on plane and radial impinging jets have been completed in the past two decades, generally with one of two objectives in mind, these being validation of a turbulence model or an investigation of the heat transfer characteristics. In the case of turbulence validation Cooper et al. [7] conducted a thorough experimental program for the evaluation of four turbulence models described in a companion paper [8]. Baughn and Shimizu [9] report experimental results in a similar vein for the heat transfer from a normally impinging jet onto a flat plate, using jets of air over a range of jet velocities.

In terms of modifications to enhance heat transfer Zumbrunnen and Aziz [10] and Sheriff and

Zumbrunnen [11] investigated heat transfer enhancements by interrupting a liquid jet, and reported an enhancement to the heat transfer occurred when the frequency of interruption was high enough. Sailor et al. [12] performed a similar investigation using air jets over a range of velocities and pulsation frequencies and again found the heat transfer to be enhanced, though at a lower threshold frequency than Zumbrunnen and Aziz [10]. Beitelmal et al. [13] studied an impinging air jet at various angles of attack as a means of modifying the distribution of heat transfer in the impingement region as well as any changes to the net heat transfer. Bilen et al. [14] investigated the variation in heat transfer distribution using multiple-channel and swirling impinging jets. Wu et al. [15] developed a micro-cooling module utilising an array of micro-jets etched into a silicon wafer, for the purpose of cooling electronic micro-chips. Amon et al. [16] reported on cooling using droplet impingement and low temperature boiling of a dielectric fluid making use of the higher rates of heat transfer available from a fluid boiling in the film-boiling region. Bart et al. [17] performed a study of the heat transfer characteristics in an array of pulsed impinging circular air jets.

Numerical and Theoretical Investigations

The normally impinging fluid jet has been subject to much numerical investigation with a large proportion of this work aimed at validation of turbulence models for fluid flows and as test cases for Computational Fluid Dynamics (CFD) codes. In these cases the emphasis is placed on the turbulence parameters and other flow parameters as opposed to heat transfer. Examples of this type of investigation include Craft et al. [8] (see also [7]), Dianat et al. [18], Behnia et al. [19], Cziesla et al. [20], Merci and Dick [21], Beaubert and Viazzo [22], and others. Other studies have, however, focused on heat transfer and including work by Shi et al. [23], Voke and Gao [24], Ooi and Behnia [25] and Chung et al. [26]. Shi et al. [23] studied the heat transfer under a turbulent slot jet for a range of jet velocities and spacings between the jet nozzle and target surface. Generally the heat transfer was overpredicted in their results while qualitatively they compared well with experiment. Voke and Gao [24] performed a numerical simulation of a confined liquid slot jet into an enclosed liquid pool using large eddy simulation for turbulence prediction. Ooi and Behnia [25] performed a numerical simulation for a circular jet impinging on an inclined plane and obtained results generally consistent with experimental values. Chung et al. [26] conducted a numerical study into an unsteady impinging air jet at low velocities and their results indicated that the unsteady effects to be significant.

Significance

While the study of impinging jets has been underway for many years now, very few correlations exist to relate heat transfer to a particular jet geometry and flow condition. One of the objectives of this research project is to move towards rectifying this shortfall by developing a correlation for impinging jets on small scales, and achieving this will be a significant contribution to the field as correlations of this nature greatly aid the design process and allow an emerging technology to move from the academic arena to an industrial one. This ultimately benefits industry by increasing efficiency and reducing costs. A second outcome of this study will be additional data supporting the currently available numerical models for Computational Fluid Dynamics, or alternatively highlight areas where these models are inapplicable or inadequate. This in turn provides a stimulus for investigation into new or improved mathematical models that more accurately represent the physical reality.

Research Method

Two distinct methods of study will be applied to the problem, the first consisting of a numerical investigation to identify the parameters which serve to enhance heat transfer for an impinging jet and the second an experimental study to provide data with which to verify and support the claims made from the numerical results.

Numerical Simulation

For the numerical component of the research the commercial Computational Fluid Dynamics (CFD) package FLUENT will be used to generate results for a range of alternative jet geometries and flow conditions. The package uses a finite control volume approach applied to 2-dimensional and 3-dimensional domains. A number of physical models are included to allow the simulation of turbulent and/or multi-phase flows, which should allow a large range of jet configurations to be studied. Shi et al. [23], Ooi and Behnia [25] and Rushyenrdran et al. [27] have reported numerical results using this package that are consistent with available experimental data. From this it is anticipated that FLUENT should be sufficient for the numerical component of the study. However if during the course of the research it becomes apparent that the package is unsuitable, alternative means will be investigated to perform the numerical component.

Experimental Work

Prior to the conclusion of the numerical work suitable areas for experimental investigation will be identified, and at this point an experimental rig will be constructed to confirm the numerical results and identify possible areas where the numerical model may be inapplicable. A proposed experimental rig is shown in figure 1, based on test rigs previously reported in the literature (see [7, 10, 28, 29]). The rig consists of a controllable pulsing air supply to be directed onto a heated surface of known (constant) heat output. The surface will have a number of thermo-couples embedded at various radii from the jet centreline to allow the surface temperatures to be measured and hence the heat transfer between the jet and the plate to be recorded. A rig similar to that shown has already been constructed for past research in the Department of Mechanical Engineering, though it is unlikely that this rig will be suitable for use without some modifications being made.

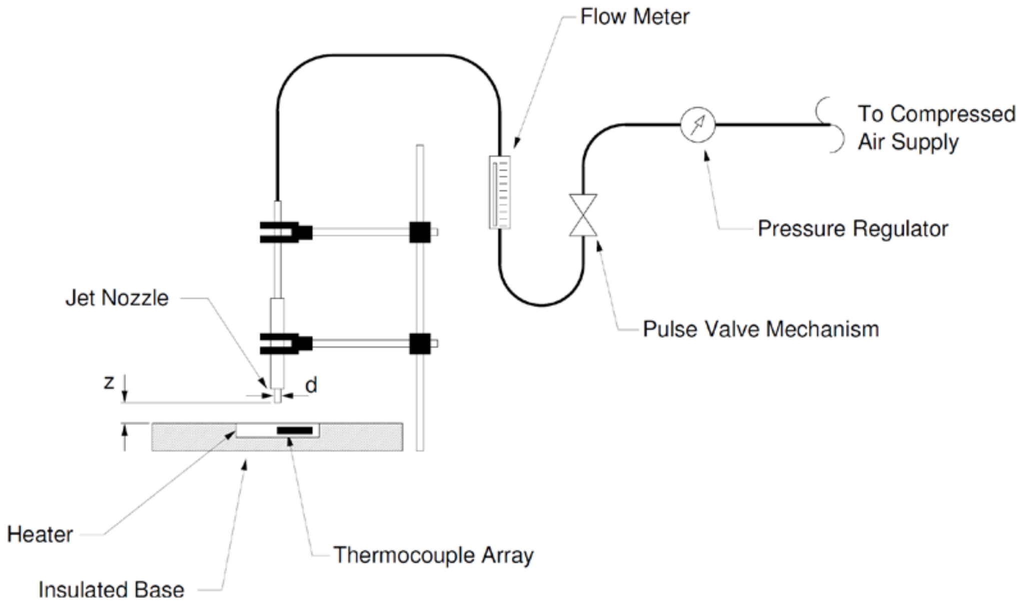

Figure 1: Layout of Jet Impingement Test Rig

Ethical Issues

It is envisaged that no ethical issues will be encountered during the course of this research.

Facilities and Resources

For the numerical component of the investigation a recent model desktop PC with a sufficient RAM is required. A CD writer will be needed to allow storage of data for the required period of seven years. For the experimental program equipment to construct a suitable experimental rig is required, though the existing test rig should provide a basic setup which can be modified as necessary. The modifications to the rig should be possible using resources available within the Department of Mechanical Engineering.

Data Storage

The data storage provisions are outlined in the attached Research Data Management Plan and meet the Curtin University Research Data and Primary Materials Policy.

Time Line

A proposed schedule for the research program is indicated below.

	Months From January 2003									
Activity	3	6	9	12	15	18	21	24	27	30
Preliminary Literature Review										
Definition of the Problem										
Preliminary Numerical Studies										
Review of Preliminary Work										
Numerical Studies										
Construction of Experimental Rig										
Collection of Experimental Data										
Data Analysis										
Thesis Preparation										

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