THERMAL HYDRAULIC PERFORMANCE OF MICROCHANNEL HEAT SINK DEVICE

NATRAH BINTI KAMARUZAMAN

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To my beloved husband Mohamad Fekrie bin Nadzeri

and

my lovely child Syamil Rahman

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ABSTRACT

The study of micro cooling heat transfer from a hot surface has been performed by using a device consisting of short micro channels. These devices have been developed by the Institute of Micro Process Engineering at the Karlsruhe Institute of Technology. The investigation was focusing mainly on the heat transfer and pressure drop problem for a single-phase flow device. The objective of this study is to achieve a compromise value of heat flux and pressure for short microchannel heat sink. An experimental rig has been developed, and a microchannel heat sink with microchannel dimensions of 800 μm width, 200 μm length and 100 μm height was tested to investigate the characteristics of the device. A simulation work has been performed using a simplified model from the actual device and was then validated with the experimental result. Further improvement has been carried out on the model and simulated to predict the most compromising value between heat fluxes, pressure drop and substrate temperature. The study has shown that the combination of multi-layer arrangements and 50 μm depth microchannels was able to increase the heat transfer rate of the device by 9.7% and decrease the pressure drop by 20%. This was achieved by using only single-phase flow and without the application of impingement jets or phase change process. The advantages of multilayer short microchannels were not only on the reduction of the pressure drop and increment of the heat transfer but also their suitability for many applications, besides the fact that they could be rearranged for small surface areas.

ABSTRAK

Kajian mengenai pemindahan haba penyejukan mikro dari permukaan yang panas telah dijalankan dengan menggunakan peranti yang terdiri daripada saluran mikro pendek. Alat-alat ini telah dibangunkan oleh Institut Kejuruteraan Mikro Proses di Karlsruhe Institute of Technology. Kajian telah memberi tumpuan kepada masalah pemindahan haba dan kejatuhan tekanan untuk peranti aliran fasa tunggal. Objektif kajian ini adalah untuk mencapai nilai terkompromi fluks haba dan tekanan untuk sinki haba bersaluran-mikro pendek. Sebuah pelantar eksperimen telah dibangunkan dan dua unit sinki haba bersaluran-mikro dengan saluran berdimensi 800 µm lebar, 200 µm panjang dan 100 µm tinggi telah diuji untuk mengkaji ciri peranti. Kerja simulasi telah dijalankan dengan menggunakan model yang dipermudahkan dari peranti sebenar dan kemudiannya disahkan dengan keputusan eksperimen. Penambahbaikan telah dijalankan ke atas model dan simulasi untuk meramalkan kombinasi yang paling optimum antara fluks haba, kejatuhan tekanan dan suhu substrat. Kajian ini telah menunjukkan bahawa gabungan penyusunan saluran mikro dengan ketinggian 50 µm yang disusun secara empat lapisan dapat meningkatkan kadar pemindahan haba peranti sebanyak 9.7% dan mengurangkan kejatuhan tekanan sebanyak 20%. Ini dicapai dengan hanya menggunakan aliran fasa tunggal dan tanpa penggunaan jet hentaman atau proses perubahan fasa. Kelebihan saluran-mikro pendek yang disusun berlapis bukan sahaja pada pengurangan penurunan tekanan dan peningkatan pemindahan haba tetapi juga kesesuaiannya untuk pelbagai aplikasi, di samping kebolehannya untuk boleh disusun semula bagi kegunaan pada kawasan permukaan yang kecil.

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LIST OF SYMBOLS

A	-	Area
a	-	Channel height
b	-	Channel width
Br	-	Brinkman number
c	-	Specific heat
D	-	Diameter
E	-	Energy
e	-	Uncertainty
er	-	Relative roughness
F	-	Force
f	-	Friction factor
h	-	Heat transfer coefficient
k	-	Heat conductivity
L	-	Channel length
m	-	Mass
$\dot{m}$	-	Mass flow rate
Nu	-	Nusselts number
P	-	Pressure
Pe	-	Peclet number
Po	-	Poiselle number
$\dot{q}$	-	Heat flux
$\dot{Q}$	-	Heating Power
Pr	-	Prandtl number
R	-	Resistance
Re	-	Reynolds number
s	-	Length
t	-	Time
T	-	Temperature
u	-	Velocity
$\vec{u}$	-	Average velocity
V	-	Volume
$\dot{W}$	-	
x	-	x coordinate
x	-	Axial distance

y	-	y coordinate
z	-	z coordinate
α^*	-	Aspect ratio
∂	-	Delta
Δ	-	Delta
δ	-	Boundary layer
ε	-	Absolute roughness
μ	-	Dynamic viscosity
ν	-	Kinematic viscosity
ρ	-	Density
∇	-	Del
*	-	dimensionless axial(thermal)
+	-	dimensionless axial(hydraulic)
app	-	apparent
blockupper	-	upper block
b	-	bulk mean
CS	-	control surface
cs	-	cross section
CV	-	control volume
fd,h	-	hydraulic entrance
fd,t	-	thermal entrance
h	-	hydraulic
hts	-	heat transfer surface
in	-	inlet
m	-	average
max	-	maximum
mean	-	bulk mean
out	-	outlet
p	-	pressure constant
pow	-	power
s	-	surface
system	-	system
t	-	thermal
therm	-	thermal
w	-	water
x	-	x direction
y	-	y direction
z	-	z direction

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Chapter 1

INTRODUCTION

1.1 Introduction

Electronics devices today has changed a room full of complex devices with very limited capabilities to a single mobile, simple and multifunctional device. The increment of device functionality also means the increment of the device's workload. The additional workload will result in more heat generated by the device. In order to handle the higher amount of heat generated by the device to maintain the temperature of the device within its acceptable operating range; a new cooling method should replace the conventional cooling system. In spite of that, the minimization of the device had required a new cooling system that must be integrated to the device itself. These lead to the need of micro cooling system.

The first study on micro cooling system was presented by Tuckerman *et al.* [1]. They discovered that by using a set of microchannel array, it is possible to remove up to 750 W heat from a VLSI device with total area of one centimeter squared. Started from this study, many industrial practitioners started to explore further on the capability of micro cooling system [2, 3].

Aiming at obtaining higher heat transfer rate, researchers are concerned with the pressure drop drawbacks as this drawback is related to the needs of additional pumping system [4]. Therefore, various attempts on finding the best compromising value between heat transfer rate and pressure drop were performed [5]. Most of the studies done were focused on modifying the microchannel itself [6].

The modification was not limited only to the geometry of microchannel, but included the modification of microchannel dimensions and arrangements [7]. In addition, some researchers put effort to determine the factors that contributed to the increment of both heat transfer and pressure drop [8-11]. With the effecting factors clearly known, some researchers tried to find the best microchannel design that advantages the heat transfer rate or pressure drop. In 2008, *Wang et al.*[12] proposed heat sink with transverse microchannel or short microchannel because of the capability of the short microchannel to transfer higher heat compared to current microchannel design. This is due to the effect of developing flow profile at the entrance channel [13]. Since then, numerous studies on the similar microchannel heat sink were performed to explore the capability of transverse or short microchannel in surface cooling [14]. However, the focus of this study will be on the short microchannel length that is less than 0.5 mm. This type of microchannel is practical since it could be scalable and easily fit to any surface area. Both experimental and numerical study is performed to obtain the characteristics of short microchannel device and to determine the most compromising value between heat transfer and pressure drop. Further review on recent development of microchannel heat sink and the factor that influences the value of heat transfer and pressure drop in microchannel is presented in Chapter 2.

1.2 Problem Statement

Electronic miniaturization has become the trend nowadays due to a huge demand from users. The heat generated from these miniature devices could reach more than 400 W/cm^2 due to the higher workload and power consumption. This heat could cause the devices to exceed the maximum operating temperature, and further on, cause the malfunction of the system. Therefore, a new micro cooling system has been developed to suit current application.

Microchannel cooling system or better known as microchannel heat sink has been widely used lately as an alternative for better heat transfer devices. It is desirable to have a microchannel heat sink with a higher heat transfer rate but a lower pressure drop at the same time. This combination is important as a way to maintain a compact system with superior heat transfer performance. However, until now, it is difficult to find the best compromise value for both heat transfer and pressure drop [1]. Most of the designs available today provide advantage either only on the heat transfer or on the pressure drop only [15-18]. Those that meets both criteria is either having a rigid design or using a certain cooling fluid that is difficult to handle and are only specific to certain applications [5, 19]. Another major disadvantage of current device is that the device is designed based on the model of a single microchannel. Therefore the thermal hydraulic performance obtained is not represented the actual performance [20, 21] and the influence of some scaling parameters that affected the performance of microchannels are not considered [22].

In this study, arrays of short microchannels with length less than 0.5 mm are developed and experimentally tested to obtain higher heat transfer rate and lower pressure drop. This type of microchannel are selected as their velocity and temperature profile of the flow are still developing and this condition shows a higher heat transfer rate compared to developed flow profile [6, 13]. A numerical simulation focused on an array of microchannels has been modeled and simulated to study the effect of microchannel dimension and arrangement to both heat transfer and pressure drop of the device.

The current study is also focusing on trying to answer the following research question.

a) Is a single phase short microchannel heat sink suitable to be used to cool a small device that dissipate heat of 400 W/cm^2 with a pressure drop of less than 100 kPa?

b) Can a three-dimensional modelling together with conventional theory be used to predict the characteristics of short microchannel devices and capable to represent the actual device characteristics?

c) How do the aspect ratio, device material and microchannel design and its arrangements affect the thermal hydraulic performance of short microchannel in heat sink application?

1.3 Objectives of Study

The main objective of this study is to develop a microchannel heat sink device with the following operating parameters: surface area of 1cm^2, pressure drop limited to 50 kPa, heat flux greater than 400 W/cm^2 and temperature difference between heated surface and coolant inlet flow of 50 ^{o}C. The specific goals of this study are:

1. To assess the effects of aspect ratio, device material, fluid inlet temperature and inlet passage design of a short microchannel on its thermal hydraulic performance as a surface cooling device.

2. To prove that a conventional theory of heat transfer and pressure drop for macrochannel device is suitable to be used to predict the thermal hydraulic performance of a short microchannel heat sink device.

3. To establish an optimum design of a short microchannel heat sink in order to achieve the desired values for both pressure drop and heat transfer characteristics of the device.

1.4 Scope of the Study

The scope of the research are as follows:

1. In this study, an experimental setup comprising of heating system, water distribution system and measurement instrumentation is developed to resemble the cooling system of electronic devices. Short microchannel heat sinks are tested on this rig.

2. A short microchannel device consisting of 128 microchannels arranged in multiple row with eight microchannels in single row is developed.The microchannels has a dimension of 200 µm length, 800 µm width and 100 µm height and structured on a surface area of 1 cm^2.

3. For the analysis of heat transfer rate and pressure drop of short microchannel heat sink, two devices with different materials, namely polymer and copper are tested. The heat flux at the heating surface, the mass flow rate of the inlet flow and the temperature of the inlet flow are varied between the range of 50 W/cm^2 to 500 W/cm^2, 20 kg/h until 80 kg/h and 10 ^oC and 60 ^oC.

4. To prove the adequacy of conventional theory of heat transfer and pressure drop to predict the thermal hydraulic performance of microchannel heat sink, a three-dimensional CFD model consist of eight microchannels in a row is designed, modeled and simulated using ANSYS workbench CFD software. A laminar boundary condition is selected for the flow profile. The variation of two parameters are taken into account, namely heat flux and mass flow rate of inlet water. The range of heat flux is between 50 W/cm^2 to 500 W/cm^2 and mass flow rate is between 20 kg/h until 80 kg/h. A SIMPLE scheme of pressure based solution using first order upwind for energy and pressure is used to solve the Navier-Stokes equation.

5. A three-dimensional model consist of two microchannels in a row is designed, modeled and simulated to study the effect of microchannel

dimensions, namely width and height to the performance of microchannel heat sink. Additionally, the effect of the device materials on the heat transfer and pressure drop is also predicted using this simulation. Three different multilayer arrangement are simulated to obtain the optimum arrangement in achieving higher heat transfer rate with lower pressure drop value.

1.5 Research Contributions

A summary of main contributions of the research are as follows:

1. A development of a microchannel testing rig especially for a single-phase system and surface cooling purposes. This rig is suitable to be used on different compact electronic devices.

2. An optimum design of a short microchannel heat sink device as a cooling system for electronic devices. A characteristic map that shows the relationship between pumping powers, thermal resistance of the device, mass flow rate and heat flux value is produced. This map can be used as a guide in selecting the operating condition for different area application.

3. A simplified three-dimensional model of a single-phase microchannel heat sink is developed with consideration of the scaling effects. The simulation data are provided to highlight the adequacy of the conventional theory to predict the characteristic of the short microchannel device.

4. Sets of simulation data that highlights the effect of microchannel dimensions, microchannel layer arrangement, material of microchannel device and the design of distribution channel on the heat transfer and pressure drop. The final design of short microchannel with an optimum value of heat transfer, pressure drop and maximum substrate temperature to inlet temperature difference is obtained.

1.6 Thesis Outline

In Chapter 1, the concept of heat transfer and surface cooling are explained. This is meant to relate the current problem of microstructured device for surface cooler with purpose of this study. The problem statement, objectives and scope of work of this study are presented in detail.

Chapter 2 reviews the studies done by previous researchers related to the topics. In contrast with macro device, some factors should be well considered when characterizing the heat transfer and pressure drop performance of microstructure devices. These included the surface roughness, conjugate heat transfer (axial heat conduction), viscous dissipation and many more. Since the device is relatively small, all these factors play important roles to the device's performance. In addition to that, the influence of microchannel dimension is also important. Therefore, many studies covered the effect of changing the microchannel's dimension. This chapter also explained the knowledge gaps in this field and the areas that are still not being addressed and explored.

In Chapter 3, the methodology of the study are explained. Experimental setup and micro cooler device that was used in this study are explicitly described. The measurement analysis that comprises the calculation for measurement uncertainties is also described. In the simulation section, two models have been designed and selected to assess the agreement between simulation and the experiment. One model consists of eight microchannels in one row which is similar to experimental device (the experimental device consists of eight rows), and the other model consist of two microchannels (simplified model). The reasons for all assumptions specified in the simulation study are described in detail. The mesh independent test conducted on the simulation model is also presented. The simulation study is focused on the aspects of temperature distribution, heat transfer coefficient, Nusselt number, channel velocity and pressure drop of the device. Additional variables involved in this study are the mass flow rate and the heat flux.

In Chapter 4, the experimental results are presented. The results mainly focus on the substrate temperature to inlet water temperature difference and the pressure drop of the device at different mass flow rates. The characteristic map for this device has also been plotted and discussed. This chapter also includes the results of simulation study on both models. A prediction of velocity vector and temperature distribution for a row of microchannel are shown and discussed. The pressure drop of the device is also plotted for different mass flow rates. The comparative study between the two different models is also shown in detail.

In Chapter 5, results of optimization study are presented. The optimization was done by changing the microchannel parameters, device design and the device's materials. Finally as a summary from those results, the new design of microchannel heat sink device are presented. In Chapter 6, a summary and conclusions suggestions for future work are discussed.

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