UNIVERSITI TEKNIKAL MALAYSIA MELAKA

# Faculty of Mechanical Engineering

# NUMERICAL INVESTIGATION OF FLOW AND HEAT TRANSFER IN MICROCHANNEL

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# NUMERICAL INVESTIGATION ON NANOFLUID FLOW AND HEAT TRANSFER IN MICROCHANNEL

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**A thesis submitted in fulfilment of the requirements for the degree of Master of Mechanical Engineering (Energy Engineering)**

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## DECLARATION

I declare that this thesis titled "Numerical Investigation of Flow and Heat Transfer in Microchannel" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not currently submitted in candidature of any other degree.

Signature : ……………………………

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**APPROVAL**

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Mechanical Engineering (Energy Engineering).

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| Date | : | ……………………………… |

## DEDICATION

To infinity and beyond.

**ABSTRACT**

A numerical study was conducted to investigate the flow of water flowing through a rectangular channel with a hydraulic diameter of 86.58 $\mu m$. A constant heat flux is applied to the heatsink top surface to investigate the cooling performance of the microchannel heatsink. The flow employed had Reynolds numbers between 140 to 1400. It was observed that within the aforementioned Reynolds number range, the water flows in laminar regiment. As the inlet velocity increased, the velocity profile took a longer path to develop. The effect of increasing Reynolds number also increased the localised Nusselt number and lowered the wall and fluid bulk temperatures. Substitution of water with $Ag$-$H_2O$ 0.5 $wt\%$ nanofluid resulted in better overall heat transfer performance in terms of wall temperature and Nusselt number. At $Re = 140$, the microchannel top wall temperature decreased as much as 3.5 $°C$ and the convective heat transfer along the walls improved between 25% to 30% for $Re = 1400$. It is recommended that future works based on this topic to increase the range of Reynolds number so that the critical Reynolds number could be determined. Experimental validation is also crucial as numerical methods cannot exactly emulate the conditions in real life application.

# ABSTRAK

Satu kajian telah dijalankan bagi menyiasat aliran air melalui saluran berbentuk segi empat tepat dengan diameter hidraulik 86.58 $\mu m$. Fluks haba sekata telah diletakkan pada permukaan paling atas singki haba untuk mengkaji keupayaan penyejukan saluran mikro. Aliran yang digunakan mempunyai nilai Reynolds antara 140 ke 1400. Melalui pemerhatian, didapati bahawa aliran air tersebut bersifat laminar. Apabila halaju masuk dinaikan, profil halaju mengambil jarak yang lebih jauh untuk terbentuk. Dengan kenaikan nilai Reynolds, nilai Nusselt setempat turut meningkat serta suhu permukaan saluran dan aliran menurun. Penggantian air dengan $Ag$-$H_2O$ 0.5 *wt%* meningkatkan prestasi pemindahan haba dari segi suhu permukaan dan nilai Nusselt. Pada $Re = 140$, suhu permukaan atas saluran mikro turun sehingga 3.5 $°C$ dan pemindahan haba konvektif meningkat antara 25% ke 30%. Kajian yang bakal dilakukan dalam bidang ini disarankan supaya menaikkan had Reynolds untuk menentukan nilai Reynolds kritikal. Pengesahan secara uji kaji adalah penting kerana kaedah berangka tidak mencerminkan keadaan-keadaan dalam aplikasi sebenar.

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| | | |
|---|---|---|
| $A_c$ | - | cross sectional area of channel |
| $C_f$ | - | coefficient of friction |
| $c_p$ | - | specific heat at constant pressure |
| $c_v$ | - | specific heat at constant volume |
| $d_h$ | - | hydraulic diameter of channel |
| $f$ | - | friction factor |
| $H$ | - | height of microchannel heatsink |
| $H_{ch}$ | - | height of microchannel |
| $H_{w1}$ | - | substrate thickness on insulated side of microchannel heat sink |
| $H_{w2}$ | - | substrate thickness on heated side of microchannel heat sink |
| $h$ | - | convective heat transfer coefficient |
| $i$ | - | number of iteration |
| $k$ | - | thermal conductivity |
| $L$ | - | length of microchannel heatsink |
| $L_h$ | - | hydrodynamic entrance length |
| $n$ | - | outer normal coordinate at interface between solid and fluid |
| $Nu$ | - | Nusselt number |
| $P$ | - | pressure |
| $q''$ | - | heat flux |

| | | |
|---|---|---|
| *Re* | - | Reynolds number |
| $r_{np}$ | - | radius of nanoparticle |
| $R_t$ | - | thermal resistance |
| $T$ | - | temperature |
| $T_{in}$ | - | fluid inlet temperature |
| $T_m$ | - | fluid bulk temperature |
| $u$, $v$, $w$ | - | velocity component in the $x$, $y$, $z$ direction respectively |
| $\vec{V}$ | - | velocity vector |
| $W$ | - | width of microchannel heat sink unit cell |
| $W_{ch}$ | - | width of microchannel |
| $W_{w1}$, $W_{w2}$ | - | half thickness of wall separating microchannels |
| $x$, $y$, $z$ | - | Cartesian coordinates |

*Greek symbols*

| | | |
|---|---|---|
| $\dot{\gamma}$ | - | shear rate |
| $\mu$ | - | dynamic viscosity |
| $v$ | - | kinematic viscosity |
| $\rho$ | - | density |
| $\tau$ | - | fluid shear stress |
| $\upsilon$ | - | velocity |
| $\varphi$ | - | volume percentage |

*Subscripts*

| | | |
|---|---|---|
| *av* | - | average |
| *bf* | - | base fluid |
| *f* | - | fluid |

| | | |
|---|---|---|
| *in* | - | inlet |
| *nf* | - | nanofluid |
| *np* | - | nanoparticle |
| *s* | - | solid |
| *w* | - | heatsink top wall |
| $\Gamma$ | - | interface between solid and fluid |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

This section describes the direction of the research and the significance behind it. The research goal is listed on the objective along with the boundary of the study. Summarisation of research outline is laid out.

## 1.2 Introduction

The rapid expansion of modern civilisation demands higher processing power for digital devices, such as computer. Consequently, the advancement of processing chips and microarchitecture skyrocketed, which in turn require more effective cooling methods. This is critical as the heat generated by electronic component severely affects the operation and degrade the component in a long run.

Myriad of cooling solutions were developed to dissipate the component heat flux. However, there are still technology gaps in microchannel cooling, particularly with nanofluid as working fluid. Combination of microchannel high surface and nanofluid thermal performance is an interesting prospect.

A commonly known challenge to this application is the scale of microchannels, which led to many inconsistencies among researchers. A numerical study on this theory shows that albeit the general acceptability of conventional theorems in microscale applications, there are large discrepancies observed on some of the flow aspects.

## 1.3 Research Background

The work on microscale cooling device was pioneered by Tuckerman and Pease (1981) that used etched microchannels with deionised water as the working fluid. In the experiment, a maximum temperature increment of 71 $°C$ was obtained for a power density of 790 $Wcm^{-2}$. Since then, the progress in this field has come a long way. One research discovered that microchannel heatsinks capable of dissipating heat flux of 1000 $Wcm^{-2}$ with only 120 $°C$ recorded maximum temperature (Roy & Avanik, 1996).

By implementing microchannel cooling systems, the main goals of electronic cooling; reduction of components maximum temperature and minimisation of surface temperature gradient could be efficiently accomplished (Garimella & Sobhan, 2003). To illustrate, a 14-*mm* cube of stacked microchannel heatsinks was able to transfer 10 *kW* of heat with only 80 $°C$ of temperature difference using only water as the working fluid (Sharp, et al., 2005).

The main attribute that enable this excellent performance is that microchannel heatsinks has a high surface area per unit volume compared to larger scale devices (Qu & Mudawar, 2002). The distinction between channel sizes in terms of hydraulic diameter, $D_h$, was pointed out by Kandlikar (2002) which stated that microchannels have a range of 10 $\mu m$ to 200 $\mu m$, minichannels between 200 $\mu m$ to 3 *mm*, and beyond 3 *mm* is classified as conventional channels. As a follow-up, the classification was further narrowed down to include transitional microchannel (10 $\mu m \geq D_h \geq 1$ $\mu m$), transitional nanochannels (1 $\mu m \geq D_h \geq 0.1$ $\mu m$), and also molecular nanochannels (0.1 $\mu m \geq D_h$) (Kandlikar, 2003).

To further enhance the understanding of microchannels, some researchers experimented with difference channel cross sectional shapes (Tongpun, et al., 2014), channel configurations (Neama, et al., 2017), aspect ratios (Sahar, et al., 2017), and the effects of shaped ribs within the microchannel (Behnampour, et al., 2017). While most researchers used water or oils as the heat transfer media, some of the published papers indicate the use of nanofluids as coolant (Chen & Ding, 2011).

Nanofluid, a term firstly introduced by Lee, et al. (1999) is a suspension that has dispersed nanosized metallic, metal-oxidic, or non-metallic particles (Zhou & Ni, 2008). The main benefit of using nanofluid as opposed to conventional fluid is the improved thermal conductivity. Nanofluids exhibit exceptional enhanced thermal conductivity through the addition of solid particles with diameters below 100 *nm* into the base fluid (Wu, et al., 2016). The key mechanism in the heat transfer performance lies within the suspension Brownian motion (Gupta, et al., 2017).

Typically, to increase nanofluid thermal performance, nanoparticles with better thermal conductivity is chosen. For example, in comparison with water, nanofluid with silver (*Ag*) nanoparticles display higher improvement percentage at 36% compared with 29% from single-walled carbon nanotube (SWCNT) (Gómez, et al., 2017). Also, by increasing nanoparticle volume concentration, the heat transfer coefficient can be improved (Togun, 2016).

Microchannels and nanofluids has wider usage other than the aforementioned applications. Other than cooling electronics, microchannels are also used in micro thrusters, biomedical detection, and other fields (Zhang, et al., 2016). Whereas nanofluids implementation can be extended to quenching process (Babu & Kumar, 2012) and for solar collector application (Koca, et al., 2017).

## 1.4 Problem Statement

Though there are many researches that focus on the liquid flow within a microchannel, many omit the hydrodynamic entrance length. Apart from that, the majority of research papers focus on the performance of nanofluids with alumina, copper, and titanium nitride nanoparticles, and few involve silver nanofluids. However, the main question is whether the flow in microchannel behave similarly to macro scale flow in terms of flow properties and thermal performance.

## 1.5 Objectives

The objectives for this study are listed as follows:

i. To simulate the fluid flow at various Reynolds number in a microchannel,

ii. To investigate the velocity profile in microchannel for water at various Reynolds number, and

iii. To compare the Nusselt number on the channel walls for water and silver-water nanofluid.

## 1.6 Boundary of Study

In this study, the method used to analyse the flow and thermal performance is computational fluid dynamics software (CFD), which is ANSYS Fluent. The working fluids that will be used are water ($H_2O$) and silver-water nanofluid ($Ag$-$H_2O$ 0.5 $wt\%$). The condition for the simulation is limited for single phase flow, at Reynolds number ranging from 140 to 1400. The microchannel have a hydraulic diameter of 86.58 $\mu m$.

## 1.7 Methodology

This numerical study focuses on the thermal and flow performance of fluid inside a rectangular microchannel with a fixed hydraulic diameter of 86.58 µm. The working fluid for the study is pure water. The Reynolds numbers were manipulated by controlling the inlet velocity, with known values of hydraulic diameter and viscosity are kept constant. Concurrently, a constant heat flux is applied at the top surface of the heat sink. As the heat energy propagates through the media, the cooling performance of both fluids were compared.

To solve these problems, numerical method using ANSYS software package was used. Due to the lack of established mathematics exclusive for microchannel flow, the general solution for thermofluid applications was employed. In this study, SIMPLE (semi-implicit pressure linked equation) particularly was used with energy equation.

Primarily, the numerical result for water was compared to the work investigated by Qu and Mudawar (2002) to establish the validity of the solution. Next, the working fluid was substituted with nanofluid of fixed properties to detect any enhancement or degradation in flow and thermal performance.

## 1.8 Report Outline

This paper titled as "the investigation of flow and heat transfer in microchannel" consists of five chapters. The next four chapters are numbered as below:

Chapter 2 (Literature Review)

Literature review is the section that discusses information related to the topic of this study. It provides the needed knowledge for the research to proceed. Prior research works were reviewed to determine the research gap and appropriate approach to achieve the study objectives.

Chapter 3 (Numerical Work)

It describes the steps and measures for this study. The specifics such as the simulation setups and microchannel heatsink design is also described in detail.

Chapter 4 (Results and Discussion)

The results and observations from the numerical works are compiled in this section. The data are presented in charts and compared to the outcome from similar researches. The reasoning and inference for the numerical study will be discussed in this chapter.

Chapter 5 (Conclusion)

This chapter is the culmination of all research work for this study. It concludes the findings, establish the key outcome of the research, and suggests future research works.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

In this segment, past research papers are reviewed to establish a sound understanding on the applicable theories and the engineering concept related to this study. Data from previous works are compiled and compared to validate numerical results in chapter 4.

## 2.2 Microchannel

Microchannel has exceptional heat rejection performance due to its ability to accommodate for high surface area in a limited volume, which is why numerous experimental and numerical studies were conducted on the flow and heat transfer properties in microchannels. Many efforts directed towards proving whether the general solution in macro scale is applicable as the flow scale decreases. The Reynolds prediction for laminar and turbulent flow was also extensively studied as well as the enhancement in terms Nusselt number distribution, as well as pressure drop and friction factors.

In a numerical study by Emran and Islam (2014), a rectangular microchannel with 231 µm and 713 µm was used to study the flow dynamics and heat transfer characteristics. An inlet temperature of 15 °C for water at Reynolds number between 225 to 1450 and a constant heat flux at the channel bottom was simulated. A declining linear pattern of pressure drop was observed throughout the channel and the highest bulk temperature recorded is at the region adjacent to the outlet.

Dirker et al. (2014) has conducted an experiment to investigate the effects of inlet geometry is on the friction factors, Nusselt numbers, and critical Reynolds number associated with a single channel of 0.57, 0.85, and 1.05 *mm* in diameter. In adiabatic case, the critical Reynolds number, $Re_{cr}$, for contraction inlet is between 1800 to 2000. Meanwhile, in diabatic cases for contraction, bellmouth, and swirl inlets, $Re_{cr}$ was found to be 2000, 1200, and 800 respectively. Conventional model was able to correctly predict the friction factor and Nusselt numbers in laminar regions.

In another experiment conducted by Zhang et al. (2014), water flowing through multiport microchannel flat tube was tested to find the flow and heat transfer characteristics. Samples tested have hydraulic diameters between 0.48 to 0.84 mm, aspect ratios 0.45 to 0.88, and relative roughness from 0.29% to 1.06%. Critical Reynolds number was found ranging from 1200 to 1600. Entrance effect has a prominent role in determining the friction factor in turbulent region, whereas the effect of aspect ratio on the critical Reynolds number is negligible. At high *Re*, the influence of roughness is more apparent although the laminar region is more influenced by entrance effect.

The flow behaviour of air in microchannel was experimentally studied by Kai et al. (2015). The study incorporated the use of copper and fibreglass microtubes with diameters of 0.2, 0.3, 0.4, 0.5, and 1.0 *mm* resulting in critical Reynolds numbers of 1100, 1300, 1600, 1800, and 2100 respectively for each diameter sizes. Simultaneously as the diameter gets larger, the rate of pressure drop becomes faster.

The practicality of using conventional flow and thermal correlations in rectangular microchannel was tested by Kim (2016). 10 rectangular microchannels ranging from 155-580 $\mu m$ and aspect ratios of 0.25 to 3.8. The working fluids, FC770 and DI water, flow within Reynolds number limits of 30 to 3500. The effect of aspect ratio, $\alpha$, is significant as it increases the critical Reynolds number from 1700 to 2400 when $\alpha$ is reduced from 1 to 0.25.