NUMERICAL INVESTIGATION OF WATER FLOWS INSIDE A MICROCHANNEL

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DECLARATION

I declare that this project entitled “Numerical Investigation of Water Flows Inside a Microchannel” is the result of my own work except as cited in the reference.

Signature: ……………………………….

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Date:…………………..2018

APPROVAL

I hereby declare that I have read this project, and, in my opinion, this report is sufficient in terms of scope and quality for the award of the Bachelor of Mechanical Engineering (with Honours).

Signature: …………………………

Name: DR ERNIE BT MAT TOKIT

Date :……………………2018

DEDICATION

To my beloved father and mother MOHD TARMIJI BIN MUKHTAR and MARIAH BINTI SELAMAT .

My supervisor DR ERNIE BT MAT TOKIT

And dear friends.

ABSTRACT

In this study, by using water as a cooling fluid, the three-dimensional fluid flow and heat transfer in a rectangular micro-channel are analyzed numerically. The microchannel have a depth of 180 µm and a width of 57 µm, and length of 10 mm. A numerical analysis is simulated using a Gambit 2.4.6 and Fluent 6.1 version. The results carefully validated by comparing the data with the other available experiment data. In terms of velocity profiles, flow Reynolds number affects the length of the flow developing region. For the higher value of Reynold number of 1500, fully developing region may not be achieved. It is also found that the temperature rises along the flow directional in the solid and fluid region can be approximately linear for the microchannel investigation. Temperature is high at the channel top wall rather than channel bottom wall with the deviation of 0.51%. At near channel inlet, the Nusselt number much more higher values and vary around the channel periphery, approaching 5 average Nusselt number.

ABSTRAK

Dalam kajian ini, dengan menggunakan air sebagai cecair penyejukan, aliran cecair tiga dimensi dan pemindahan haba dalam Mikrochannel segi empat tepat dianalisis secara berangka. Mikrochannel mempunyai kedalaman 180 µm dan lebar 57 µm, dan panjang 10 mm. Analisis numerik disimulasikan menggunakan Gambit 2.4.6 dan versi Fluent 6.1. Hasilnya disahkan dengan membandingkan data dengan data eksperimen lain yang tersedia. Dari segi profil halaju, aliran bilangan Reynolds mempengaruhi panjang aliran wilayah yang sedang berkembang. Bagi nilai Reynold yang lebih tinggi daripada 1500, rantau membangun sepenuhnya tidak dapat dicapai. Ia juga mendapati bahawa suhu meningkat sepanjang arah aliran di kawasan pepejal dan bendalir boleh menjadi kira-kira linear untuk penyiasatan mikrochannel. Suhu tinggi di dinding atas saluran berbanding dinding bawah saluran dengan perbezaan 0.5%. Di dalam saluran masuk berhampiran, nombor Nusselt mempunyai nilai yang lebih tinggi dan berbeza di sekitar pinggir saluran menghampiri 5 purata nombor Nusselt.

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CHAPTER 1

INTRODUCTION

1.1 Background

Geometry, surface roughness, flow velocity, surface temperature, and type of fluid affect the transition from laminar to turbulent flow inside a microchannel. According to Osborne Reynolds (Cengel & Cimbala, 2014) in 1880 by injecting some dye streaks into the flow in a glass pipe, the author discovered that the flow regime depends on the ratio of internal forces to viscous forces in the fluid that is now called Reynold number. Critical Reynolds number, Re_{cr} is the Reynolds number at which the flow becomes turbulent. For internal flow inside the circular pipe, the Re_{cr} is on 2300. Reynolds number is based on the hydraulic diameter D_h of the pipes. Under the most practical conditions by considering all degree of disturbance of flow by surface roughness, pipe vibrations and fluctuations in the upstream flow, the critical Reynolds number was under transitional flow from 2300 to 4000 Reynolds number.

Small channel measurement studies separated the ranges from 1 µm to 100 µm as a microchannel, 100 µm to 1 mm as meso-channels, 1 mm to 6 mm as reduced entries, and more than 6 mm as compact passages. This group is essentially based on the size of the channel build (Mehendale, Jacob, & Shah, 2000). Classification of flow based on Knudsen number is used for providing a classification scheme for microchannel, small channels, and conventional channels. For this purpose, means normal gas free pathways such as oxygen, nitrogen, and hydrogen near

1 atmospheric pressure is considered. (Satish G. Kandlikar, 2003) classifies its conventionnel channel with more than 3mm its hydraulic diameter. Otherwise, mini-channels from range 3mm to 200µm and microchannel from 200 µm to 10µm. They are prescribed for both liquid and in addition two-phase flow applications to give a consistency in channel characterization.

The velocity profile shows in Figure 1.1 to know the nature of the fluid flow inside a channel. By considering fluid enters circular pipe at a uniform velocity, in no-slip condition, the fluid particle in the layer is completely stopped in contact with the wall of the pipe. In boundary layer region, viscous effects and velocity changes are significant. Otherwise, in irrotational flow region, the frictional effect is negligible, and the velocity remains essentially constant in radial direction. When the velocity profile is fully developed and remain unchanged, it's called hydrodynamically fully developed region. When the fully developed average velocity profile is flatter or fuller, it's totally in turbulence flow. Otherwise, when parabolic, it's a laminar flow (Cengel & Cimbala, 2014).

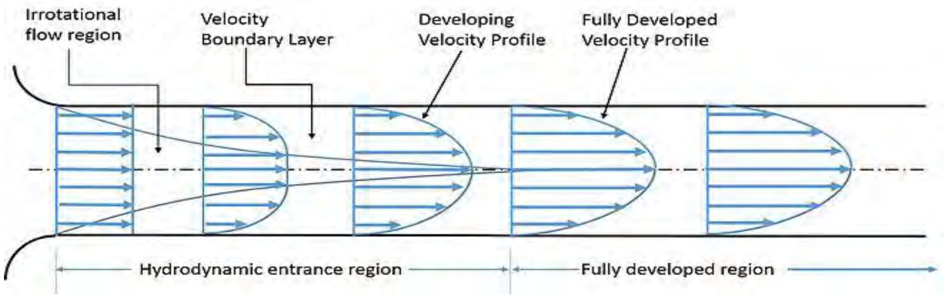

Figure 1.1: The development of the velocity boundary layer in pipe (Cengel & Cimbala, 2014).

Therefore, the aim for this study is to numerically investigate the water flow inside a microchannel. The solid substrate used is copper and water as coolant fluid. The distribution of average temperature and average Nusselt number inside a microchannel been analyze.

1.2 Problem Statement

Theoretically, the critical Reynolds number for internal flows in the circular pipe is 2300. But in some cases, the critical Reynold number can be low as 1700 to 2400. This indicates that the laminar flow region is below the Reynolds number of 1700. The velocity profile for laminar region in the fully developed region is parabolic while turbulence much more flatter and fuller. Therefore, there is a need to verify in the fully developing region either the parabolic velocity profile in the laminar flow is applicable for water flow inside a microchannel.

1.3 Objective

The main objectives of this project are:

1. To simulate the water flow at various Reynolds number in laminar flow.
2. To investigate the velocity profile of water flow at various Reynolds number

1.4 Scope

The performance of the microchannel is analyzed using Computational Fluid Dynamic (CFD) FLUENT 6.1 software. The scopes of this project are:

1. For the microchannel, the hydraulic diameter range of 10 µm – 200 µm and from 1000 to 1500 for the Reynolds number.
2. This research is simulated using a software known as Gambit and Fluent. Only velocity profile of water flow is examined.
3. Only water as working fluid used in the study.

1.5 General Methodology

The actions that need to be carried out to achieve the objectives in this project are listed below.

1. Literature review:

   Books, journals, article and all another alternative reference for this project.
2. Design Drawing:

   The sizing of microchannel using Gambit geometry and mesh generation software.
3. Simulation:

   Simulation of the water velocity profiles using Fluent software based on the various of Reynolds number.
4. Analysis

   The velocity profiles pattern result is analyzed to get the value of the critical Reynolds number.
5. Report writing:

A report on this study is written at the end of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A literature review is a search and evaluation of the available paper or research to the chosen subject. This include the survey of the chosen area of study, synthesizes the information in that literature into a summary, critically analyze information gathered by identifying gaps in current knowledge by showing the limitation and point of views and the formula used in controversial area, where the literature is expressed in an organized way. For this section, all information on the latest research about a way to gathering the critical Reynolds number, laminar, transition and turbulence fluid flow, a factor that influence the critical Reynolds number, and summary of the past literature of study. Other than that, it shows the method used to get the critical Reynolds number in the study.

2.2 Critical Reynolds Number

Investigation of fully developed of liquid and vapor flow through the rectangular microchannel had been done by (Hrnjak & Tu, 2007). The hydraulic diameter used varies from 69.5 to 304.7 µm with the aspect ratio changing from 0.09 to 0.24. Testing fluid, R-134a liquid, and water vapor were used, and the Reynold number varied between 112 to 9180. Experiment was conducted with the surface roughness of 0.21 to 0.48. For the laminar region, turbulent region and transition region, the friction factor was characterized by using pressure drop data. The author claim that even in the smallest channel test, both laminar friction factor and critical Reynold number approximate the conventional value when the surface roughness was low. As a result, the critical Reynold number range is2150 – 2290 for the smooth surface. They also determine that critical Reynold number and laminar friction factor are both significant toward the conventional value when the surface roughness becomes low. As a suggestion, the authors propose that surface roughness were responsible toward the transition to turbulent become early.

An experiment of pressure drop measurement in a microchannel was conducted to a greater understanding of flow in the small channel. The result produced were different compared to the theoretical in a future study of the friction factor for testing fluid of water and transition Reynolds number in rectangular microchannel. The Reynolds number in between 60 – 3450 in a high aspect ratio channel, a hydraulic diameter range of 252 to 973 with depth ranging from 128 to 521 µm and fixed width of 1-cm. The microchannel surface roughness was classified as smooth and a mean surface roughness 1.9 µm of polycarbonate/polyimide, maximum peak value height approximates 14.67 µm and relative roughness of 0.74%. Excluding entrance and exit losses, the pressure drop was measured within the channel itself and the transition from laminar to turbulence was observed with flow image. As a result, the transition value becomes lower than the conventional critical Reynolds number that in range of 1700 to 2200 (Pfund, Rector, Shekarriz, Popescu, & Welty, 2000).

Another experiment was conducted to measure the friction factor of laminar flow of deionized water in smooth silicon microchannel of the trapezoidal cross-section with a range of the hydraulic diameter 25.9 to 291.0 µm. Thirteen different trapezoidal silicon microchannel were observed. It was shows, the cross-sectional aspect ratio effects the friction constant of this microchannel. They also prove that Navier-stokes equation that follows non-slip condition was still applicable for deionized water flow in smooth silicon microchannel in 25.9 µm hydraulic diameter. For smooth channel but high hydraulic diameter of 103.4 to 291.0 µm, the Reynolds number of 1500 to 2000 was found as the transition from laminar to turbulent (Wu & Cheng, 2003).

An investigation of an experiment of the heat transfer and pressure drop in a rectangular microchannel was performed for water in the laminar and transitional regimes for 3 different inlet configurations. Inlet type consists of 0.57 mm, 0.0.85 mm and 1.05 mm hydraulic diameter under consideration of sudden contraction, bellmouth and swirls inlet type. From the experiment, it was found that critical Reynold number and the transition behavior influences by the inlet type. As a result, the critical Reynolds number was in the range of 1800 to 2000 for the unexpected contraction inlet type and the adiabatic friction factors. For diabatic cases, the transition regime starts at 2000 Reynolds number. Both adiabatic and diabatic consist of 2.3 µm surface roughness and 0.0022% of relative roughness. For bellmouth inlet type, the adiabatic transition started at 1250 Reynolds number while diabatic start at 1200. Bellmouth inlet is much smoother than contraction inlet type. Lastly, for swirl inlet type, a major transition occurs on 1600 Reynolds number while minor adjustment occurs at Reynold number 800 (Dirker, Meyer, & Garach, 2014).

Surface roughness within the microchannel seems to have a significant effect on flow behavior at the microscale. Flow transition from laminar flow to turbulent flow at the microscopic level must be studied in greater details so that one may accurately predict at which value of Reynolds number this transition occurs for all wall roughness's.(Hassan, Phutthavong, & Abdelgawad, 2004)

An experimental and numerical analysis of a single-phase flow through the rectangular microchannel of water in the range of the Reynolds number in between 300-3500. Hydraulic diameter considers between 318 μm to 903 μm. The microchannel width ranged from 194 μm to 534 μm, with the depth, was five times in each case. Copper was used as test piece with contained 10 microchannels in parallel. The fluid test used was deionized water. Based on the result, the transition occurs at Reynold number of 1500 to 2000. At this moment, the result showed slope, reflecting a transition from the laminar flow (Lee, Garimella, & Liu, 2005).

A three-dimensional model has been developed in order to investigate the conjugate heat transfer in a microchannel heat sink. The development of the velocity and temperature field was considered, and the approximation of fully developed flow was eliminated. Due to the combined of convection-conduction effects in the three-dimensional setting, the unusual heat transfer pattern was obtained. As a result, the average channel wall temperature along the flow direction was nearly uniform except in a region that near the channel inlet, were founded that a very large temperature gradient. (Fedorov & Viskanta, 1999)

A three-dimensional numerical simulation of the laminar flow and heat transfer of water in silicon microchannel with non-circular cross-sections were perform. To discretize the governing equation, the finite volume method was used. As a result, inside a microchannel with the sizing of hydraulic diameter of tens of micrometer of liquid flow, the Navier-Strokes and energy equations and the no-slip boundary condition based on the continuum assumption are valid and can be used for more investigation on predicting the flow and heat transfer characteristic with reasonable accuracy. Other result shows for the microchannel simulated the heat transfer intensity of triangular microchannel much less than trapezoidal microchannel, indicationg the great effect of geometric condition in microchannel system. For the increasing of Reynolds number, the fully developed region of Nusselt number is increased to.(Li, Tao, & He, 2006)

The experimental study of the full development and heat transfer in rectangular microchannel were performed. The study was to explore the theoretical collaboration to predict the fluid flow and heat transfer characteristic in microchannel based on the conventional sized channel. 10 different rectangular microchannel with hydraulic diameter around 155 to 580μm and aspect ratio of 0.25 – 3.8 with Reynolds number ranged from 30 to 2500 investigated on flow resistance and thermal behavior of the laminar flow. The experiment was conducted by using FC770 and deionized water. The conventional Poiseuille flow theory was matched up with the single-phase laminar friction factor in the microchannel. The test apparatus consists of the pressure tank, compressed nitrogen gas supply, micro annual gear pump, filter, two Coriolis mass flowmeters, the test section in which 10 different microchannels is arranged, several valves to regulate the flow rate, recovery tank, and instrumentation. A pressure tank that stainless-steel type with 40 liters holds a capacity of the working fluid (FC770 and deionized water). The test section consists of 10 different microchannel. As a result, they verified that the critical Reynolds number was increased from 1700 to 2400 with the decreasing of the aspect ratio from 1.0 to 0.25 in a rectangular microchannel (Kim, 2016).

Only for the large-sized channel were valid for some of the results of the experiment and pressure drop through the microchannel evidence. For hydraulic diameter less than 1mm, it's not applicable. It's also found that the Reynolds number for the transition is lower than the expected result. The experimental result of the laminar to turbulence in microchannel been elaborate by using Obot-Jones model for large sized model. The model was etched on the silicon wafer, with the shape of the microchannel that trapezoidal, hexagon and rectangular was considered. They claim that critical Reynold number takes place in a range of 300 to 2000. As result of Obot analyze, they realize that for the less than 1000 Reynolds number, the critical Reynold number are not strong experimental evidence. As the conclusion, using Obot-Jones method, they verify that for hydraulic diameter 40 μm and above, its applicable to predict the laminar to turbulence flow transition (Morini, 2004).

An investigation study of the behavior of the flow transition in the rectangular microchannel by using numerical simulation. Three models were adopted, namely a γ-Reθt transition model, shear stress transport (SST) model and laminar model. The simulation was conducted using ANSYS CFX and the result was compared to the conventional one. The effect of length to diameter ratio was studied on the critical Reynolds number were study. As a result, based on the 3-model flow that been tested, only γ-Reθt transition model capture the range of the Reynold number away from the conventional based on the experiment data. For the ratio of length to diameter more than 100, transition occurs in Reynolds number of 2000 to 2500, but the length to diameter ratio has no significant effect on the critical Reynolds number. It's also been suggested to eliminate the influence of the entrance effect (Jian, Li, & Zhu Zhibing Zhi and Tao, 2017).

A single-phase flow pressure drops and heat transfer in rectangular metallic microchannel were investigated using FLUENT 14.5 in numerical simulation. A single channel with a hydraulic diameter of 0.561 mm as one of the configuration simulated. A multichannel configuration consists of inlet and outlet manifold and 25 channels with a hydraulic diameter of 0.409 mm. The result of single-channel configuration valid only for water while multichannel configuration valid using experimental data of R-134a refrigerant. As result, the transition from laminar to turbulent occur on 1600 to 2000 Reynolds number. (Sahar et al., 2015)

An investigation of water in smooth and rough silicon microchannel were conducted. By using water as testing fluid, the hydraulic diameter used to range from 153 µm to 191 µm. The rectangular roughness element mounted on the wall were 50 µm high and wide. The field measure from Reynold number 100 – 2300. The velocity profile was conducted using microscope particle image velocimetry (micro-PIV) shows that transition occurred between 900 – 1100. As suggestion, the fluid flow becomes developed fully turbulence for Reynold number more than 1400 at the rough microchannel. (Zhu, 2006)

The friction factor in the transition region flow water flow in minutes and microtubes were investigated. The single-phase water flow was performed for twelve stainless-steel tubes diameter ranging from 2083 µm to 337 µm. As a result, the transition from laminar to turbulence is 1300 to 4000 Reynolds number. The Reynold number range for transition flow become narrower with decreasing tube diameter. (Ghajar, Tang, & Cook, 2010)

The liquid flow in microchannel was investigated in form of experiment and numerical method by using hydraulic diameter from 244 µm to 974 µm at a range of Reynold 230 to 6500.

As result, they agreed on the argument that developing fully turbulence flow is retarded in the microchannel and critical Reynolds number is approximately at 2000 (Liu & Garimella, 2004)

Moreover, the surface roughness effect studies on the flow behavior and heat transfer characteristic in a circular microchannel with 0.4 mm diameter and 10 mm length. the surface roughness is 0.86, 0.92,1.02 µm with a range of Reynolds number starting at 150 to 2800. As a result, the roughness is significant on effecting the flow circulation in the microchannel. the critical Reynold occur at 1500. For heat transfer properties, increasing Reynold number is increased the Nusselt number, higher roughness is contributed to higher Nusselt's number. (Yuan, Tao, Li, & Tian, 2016)

Three-dimensional fluid flow and heat transfer in a microchannel heat sink are analyzed numerically using water as cooling fluid. 1 cm^2 silicon wafer was used as heat sink. Microchannel consist of 180 µm depth and 57 µm width and separated with 43 µm wall. The SIMPLE algorithm is used to solve governing equation. Increasing Reynolds number increases the length of the developing region (Qu & Mudawar, 2002). Table 2.1 and Table 2.2 shows the summarizes of critical Reynolds number determined from previous works.