COMPARISON OF LAMINAR AND TURBULENT MODEL OF NANOFLUID FLOW IN MICROCHANNEL

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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**A thesis submitted
in fulfilment of the requirement for the degree of
Bachelor of Mechanical Engineering (with honours)**

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2018

DECLARATION

I have declared that this thesis entitled "**Comparison of Laminar and Turbulent Model of Nanofluid Flow in Microchannel"** is the result of my own word except have cited as in the references and quality for the award for degree of Bachelor of Mechanical Engineering (with honours).

Signature : ....

Name : ....

Date : ....

DEDICATION

I would like to dedicate my thesis to my beloved father and mother, Hamzah Bin Ibrahim and Maznah Bt Ishak

My supervisor, Dr Ernie Bt Mat Tokit

And dear friends

APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfilment for degree of Bachelor of Mechanical Engineering (with honours).

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Supervisor’s Name : ....

Date : ....

ABSTRACT

This study compared the nanofluid flow and heat transfer in microchannel using laminar and turbulence model. The simulations work is done using ANSYS and Fluent softwares. The nanofluid used is alumina, Al_2O_3 with 100nm size particles and 1% volume concentrations as the cooling fluid. The heat sink for the rectangular microchannel consists of 1 cm^2 silicon wafer. The channel size is 180µm, width 57µm with the length 10mm. This microchannel are separated by the 43µm gap. The simulations performance is to evaluate fluid flow and heat transfer in terms of temperature profile, heat transfer, velocity profile, entrance length and Nusselt number for both laminar and k-εpsilon model. From the simulations results, the temperature rises along from the inlet to the outlet of the channel. The higher temperature are predicted at the heat sink top wall at the channel outlet. The temperature increases the linearly along the channel for the solid and fluid regions. At the channel inlet, the higher value for the Nusselt number is predicted, then decrease until approaching constant value. The entrance lengths for the k-εpsilon model is shorter compared to the laminar model due to the early fully developed. The velocity gradient for laminar much higher compared turbulence. The percentage error of entry length are predicted between laminar and turbulence models which are 18.23% and 4.6% respectively. The percentage deviation of Nusselt number between laminar and turbulence models are predicted to be 146.77% and 28.75% respectively.

ABSTRAK

Kajian ini membandingkan aliran nanofluid dan pemindahan haba di saluran mikro menggunakan model laminar dan pergolakan. Kerja simulasi dilakukan dengan menggunakan perisian ANSYS dan Fluent. Nanofluid yang digunakan ialah alumina, Al2O3 dengan zarah saiz 100nm dan kepekatan isipadu 1% sebagai cecair penyejuk. Sinki haba untuk saluran mikro segi empat tepat terdiri daripada wafer silikon 1 cm2. Saiz saluran adalah 180µm, lebar 57µm dengan panjang 10mm. Microchannel ini dipisahkan oleh jurang 43µm. Prestasi simulasi adalah untuk menilai aliran bendalir dan pemindahan haba dari segi profil suhu, pemindahan haba, profil halaju, panjang pintu masuk dan nombor Nusselt untuk model laminar dan k-epsilon. Dari hasil simulasi, suhu meningkat dari salur masuk ke salur keluar saluran. Suhu yang lebih tinggi diramalkan pada dinding atas sinki haba di saluran saluran. Suhu meningkatkan linear di sepanjang saluran untuk kawasan pepejal dan bendalir. Di salur saluran, nilai yang lebih tinggi untuk nombor Nusselt diramalkan, kemudian berkurang sehingga menghampiri nilai malar. Panjang pintu masuk untuk model k-epsilon adalah lebih pendek berbanding dengan model laminar disebabkan oleh perkembangan awal. Kecerunan halaju bagi laminar lebih tinggi berbanding pergolakan. Kesalahan peratusan panjang kemasukan diramalkan antara model laminar dan pergolakan yang masing-masing 18.23% dan 4.6%. Peratusan peratusan nombor Nusselt antara model laminar dan pergolakan dijangka masing-masing sebanyak 146.77% dan 28.75%.

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LIST OF ABBREVIATIONS

d_h	-	Hydraulic Diameter
H_{ch}	-	Height of microchannel
H_{w1}	-	Substrate thickness on insulated side of microchannel heat sink
H_{w2}	-	Substrate thickness on heated side of micro- channel heat sink
k	-	Thermal conductivity
Nu	-	Nusselt number
q”	-	Heat flux
Re	-	Reynolds number
T	-	Temperature
T_{in}	-	Fluid inlet temperature
T_m	-	Fluid bulk temperature
W	-	Width of micro-channel heat sink unit cell
W_{ch}	-	Width of micro-channel
$W_{w1,w2}$	-	Half-thickness of wall separating micro- channels
µ	-	Dynamic viscosity
ρ	-	Density

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nanofluid is a mixture that usually made from two or more different substances with the two-phase flow. This fluid contains a small size of particles. Nanofluid also called nanoparticles. These fluid are produced by dispersing the particles in a fluid base for example water, oil and ethylene alcohol. Nowadays, nanofluid are widely used in biological, pharmaceuticals, lubrication industries and transportation. According to Akbar et al., (2017), this nanofluid plays as important part in the transportation as a coolant. The nanofluid provides the best efficiency in heat transfer, for example engines, pumps, radiators and small other components. Small vehicles can travel long distance using a little fuel. This will lead to less pollutions.

According to Kai & Peter (2014), nanofluid possesses enhanced thermophysical properties such as higher thermal conductivity and convective heat transfer coefficient as compared to the base fluid which is water. Nanofluid has the high quality of thermal properties and interesting potential applications. The nanofluid is much more stable thus make it attractive to the solution of cooling application.

Microchannel is a channel that a usually used in microtechnology. Micro means the channel with small size and small volume. Commonly microchannel has a hydraulic diameter below 1mm. Microchannel is one of the example of the microfluidics. Microchannel heat sink is a transfer of heat using a small channel. This channel used as the passage for the nanofluid to flow. According to (Manay & Sahin, 2016), nowadays technology development have increase such as developed devices which become smaller, faster and more powerful. Due to that performance, thus that devices will reach higher temperature value. Thus, this microchannel become good alternative as a cooling system.

In fluid mechanics, the boundary layer is a thin layer of fluid flow between the surfaces of solid for example surface inside the pipe and the fluid where the effect's viscosity is significant. There are three types in boundary layer which is laminar, transition and turbulent. This three types of boundary layers can be determined by the value of the Reynolds number which are laminar, transitions and turbulence. Reynolds number is the most important of the dimensionless quantity. Reynolds number are used to identify the different patterns fluids flow. Reynolds number contain three patterns which are laminar, transitions and turbulent. At low Reynolds number flow which is below 2000 is laminar "streamlines". At high Reynolds number flow which is over 4000 is turbulent "sinuous". The transition is between laminar and turbulent. Normally turbulent are most for the piping systems. Critical Reynolds number is a changing of flow from laminar to turbulent. The higher critical Reynolds numbers are depends on the upstream condition. The lower critical is value less sensitive. Values for the smooth circular pipes and tubes are below 2000. Critical Reynolds number is the Reynolds number which become turbulent. For internal flow inside circular pipe, the critical Reynolds number can be occurs on 2300. For the flow non-circular pipes, the Reynolds number are depend on the hydraulic diameter, Dh. (Cengel & Cimbala, 2014, pp. 347–352).

As we can see, in this study is all about the comparison of the laminar and turbulence flow for model inside microchannel. Then, the discussion about the fully develop flow for the laminar and turbulent inside the channel. Next, to find the entrance of fully developed regions and make comparison between laminar and turbulence. Next, the comparison between laminar and turbulence with theoretical value of Nusselt number.

1.2 Problem Statement

Flowing of nanofluid through rectangular microchannel can be identify through some process based on its parameter and thermal-physical properties. The laminar becomes turbulence flow at the critical Reynolds number. Does the critical Reynolds number are applicable for the nanoflow in microchannel analysis. The results will be difference for each difference of the geometries and flow conditions. Internal flow for the laminar flow are flowing in regularly and arranged along the channel. The energy and momentum will be transfer by molecules diffusion. For the turbulent flow, the flowing motions are in swirling like a whirlpool in transportation of mass, momentum and energy to other region. This is much faster and swiftly than molecular diffusion. Whenever the flow is steady, the whirling motion still causes fluctuations in values of velocity, temperature, pressure and density. So, the turbulence flow will link with the high value of friction, heat transfer and mass transfer coefficients.

1.3 Objectives

The following objectives of this study are:

i. to determine the entrance length,

ii. to determine the velocity gradient, and

iii. to determine the Nusselt number

of nanofluid flow using laminar and k-epsilon model.

1.4 Scopes

The scopes of this study are based on the following based parameter:

i. The microchannel is rectangular with hydraulic diameter of 86.58 µm.
ii. The Reynolds number of the nanofluid flow is 500.
iii. The turbulent model used is k-epsilon.
iv. The nanofluid used is laminar with 100nm particles and concentration of 1%.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to make a comparison between laminar and turbulence flow inside microchannel. The comparison will make based on value of Nusselt's that will get from the simulations. Next, the comparison between simulation and theoretical for the value of entry length. Then, the discussion for the fully develop of nanofluid inside rectangular microchannel. This chapter to provide a clear view about the concepts for laminar and turbulent flow and makes the theory easier to be understand.

2.2 Nanofluid Characteristics

Nanofluid have shown many curios properties in few decades. It became well-known due to widely used in industries, biomedical and so on. Nanofluid have found to acquire highly thermophysical properties such thermal conductivity and heat transfer coefficient.

Based on (Wang, Xu, & S. Choi, 1999), the thermal conductivity of the nanofluid will increase by decreasing the size of particles. By increasing the pressure drops, it’s also same as increasing heat transfer. Based on (Momin, 2013), value for temperature changes will showing the changing by the presence of the nanoparticles of the nanofluid. The higher particle volume concentrations, so the Nusselt number will decrease for the horizontal inclination. However, for the vertical inclination, by increasing of particle volume concentration (0% to 4%), it shows that the Nusselt number remain constant.

2.3 Critical Reynolds Number and Its Significant

Reynolds number is a ratio between inertia forces to viscous force. This signify flow whether bounded or unbounded. This also show the pattern of flow such as turbulent or laminar. This flow depend on the property of fluid, characteristic or equivalent diameter. The critical Reynolds number functions as determination of flow from laminar to turbulence. The critical Reynolds number is to provide condition in boundary flow become turbulent from the laminar. This depend on the density, velocity, and viscosity of fluid in flow. This flow with respect to the surface and a characteristic length for example pipe. Transitions of turbulent also depend on the surface roughness.

Re (Reynolds number) for circular and non-circular channel.

Re < 2000; signify laminar flow,

2000 < Re < 4000; signify transition flow,

4000 > Re; signify Turbulent flow.

Reynolds (1883) with the classic experiment which is dye visualisation, it was proposed to differentiate of the criterion between laminar and turbulent flow for example in pipe flow. From the experimental studies, the results show value for the critical Reynolds number is 2100.

$$Re = \frac{DVp}{\mu}$$

Where : D = The hydraulic diameter of pipe (m)

v = The kinematic viscosity (m^2/s)

p = The density of the fluid (kg/m^3)

μ = The dynamic viscosity (kg/m.s)

At low Reynolds number usually dominated by the viscous effects, are commonly laminar flow. This laminar flow are typically with dynamic action and more stagnant. At higher Reynolds number which is turbulent with a lot slight and large whirl motion. Next, from the Reynolds conclusions, he found that there must be another critical velocity. Reynolds have done experiment by the measuring the pressure drop of some length to determined critical velocity. From the result of experiment, he found that for low speed the pressure loss must be proportional to the first power of velocity and must be varying with higher power that beyond to the lower critical velocity.

Akbarinia, Abdolzadeh, & Laur (2011) have done experiment analysis about the enhancement of the heat transfer by adding the nanofluids in microchannel with constant Reynolds number. The flow for nanofluid is laminar, steady stated and incompressible. The value Reynolds number are depends to the kinematic viscosity and inlet velocity of the nanofluid. By increasing the volume fractions in nanoparticles, the kinematic viscosity of nanofluids will increase. From that, results stated the flow for the nanofluid is laminar.

Zhang et al. (2016), have done the study about the flow resistance in laminar flow by using low Reynolds number in microchannel. The value for Reynolds number is between $10^{-5} < Re < 10^{-2}$. Under the condition of low Reynolds number, the flow for the Newtonian is consistent in a smooth microchannel sized with the classic theory for laminar flow.

Majid, Mostafa and Alireza (2014), have done the numerical study about the turbulent flow for the nanofluid which is alumina Al_2O_3 inside the horizontal tube. The results of the study were compared between the experimental model and data and have been acceptable. From the result of the study, it shows that Nusselt number are depends on Reynolds number. By increasing Reynolds number, the Nusselt number will increasing.

Aghaei, Sheikhzadeh, Dastmalchi, & Forozande (2015), investigate the effect volume fractions of the nanoparticles on the average Nusselts number, skin friction factor and pressure drop. The results show that average Nusselt number depend on Reynolds number. By increasing value Reynolds number, will increase the average Nusselt number at all volume fraction. This result can be accepted because of the increasing in conductivity of nanofluid. The other causes is due to acceleration random motion of nanoparticles. Next, the skin friction factor is vary with the Reynolds number. As increasing the Reynolds number, the skin friction factor will decrease.

Rimbault, Nguyen, & Galanis (2014), has done the experimental on investigation of the hydraulic and thermal fields of a CuO water nanofluid (0.24%, 1.03% and 4.5%) flowing inside a microchannel heat sink at various volume fraction under both laminar and turbulent flow. From the study, the result shows for CuO-water have same as water for laminar-turbulent transition behaviour. The transition has occurs at the value of critical Reynolds number which is 1000. Thus, this is due to the surface roughness of the microchannel heat sink

Qu & Mudawar (2002), investigate of the fluid flow that use water a cooling fluid and heat transfer in a silicon rectangular microchannel heat sink. The result shows that the temperature rise which is flow nanofluid along channel can be approximated as linear flow. The length for the developing region is depend on the Reynolds number. As increasing Reynolds number will increase the length of the developing region. But, fully developed flow cannot be achieved at high Reynolds number. This is due to the Reynolds number affected by the thermal conductivity as it approaching to the channel outlet.

So, in this study will discuss about to determine the entrance length and velocity gradient at the fully developed regions. The discussion about the Nusselt number. This Nusselt number are depends on the Reynolds number. **Table 2.1** shows the result of critical Re determined by previous researchers.

Table 2. 1 : The result of critical Re determined by previous researchers.

Author	Nanofluid	Hydraulic Diameter	Results	Remarks
Sohel et al	Cu-H2O, Cu-EG, Al2O3-H2O, Al2O3-EG	200, 400, 600 µm		Diameter increase, thermal entropy rates generation increase
Rimbault, Nguyen, & Galanis	CuO - water	29 nm	Critical Re = 1000	Both nanofluid show similar laminar-turbulent transition behaviours as water.
Zhang	nanofluids Al203	5.0 µm - 17.4 µm	Re = 600 - 20000	Pr = 5.7-7.3, nusselt correlation to Pr num.

Khafeef & Albdoor	Al_2O_3-H_2O and Cu-H_2O	width = 57 µm depth = 180 µm, Separate wall = 43 µm	Re = 100-400	Both heat transfer and pressure drop increase, with increasing Re, while the friction factor of the MCHS is increase
Jung, Hoo and Kwak	Aluminium dioxide, Al_2O_3	170 nm	Re correlated to thermal conductivity of nanofluids.	Investigate the effect of the volume fraction of nanoparticles to convective heat transfer and fluid flow in the microchannel
Yu et al.	Methanol	57 µm - 267 µm	Re = 50 - 850	Transition does not exist at the arly laminar

CHAPTER 3

METHODOLOGY

3.1 Introduction

Nowadays, with development of sciences, people or industry have produced many types of product with more complex. They realizes that with the decreasing of size give more advantages. More compact more advantages with more functionalities. Researcher have been explored the advantages of the nanofluid and microchannel. Nanofluid functioning as the cooling media, vehicles cooling, and biomedical applications. The ability of nanofluid itself regarding to its parameter such as thermal conductivity and heat transfer compared to the base fluid. The research focusing on the effect of the nanofluid on boundary layer inside the microchannel. Thus, this methodology have been done to get more overview about this simulations studies and give detail description on how the project is conducted.

3.2 Flowchart

To obtain the objectives of this studies, the step of the flowchart are followed:

i. Literature review: The reference from all sources such as journal and articles that are related to this project will be reviewed and studied. This are needed to ascertain the objectives.

ii. Domain design and model mesh: Design and meshing the rectangular microchannel heat sink using GAMBIT software according to the dimensions. Discretizing by giving the grids to the geometry. Setup the boundary for example inlet, outlet, fluid, solid and wall.

iii. Mesh independence test: Meshing the model with different meshed size at the size wall or y-direction. The different meshes are **40 × 25 × 150**, **45 × 25 × 150**, **50 × 25 × 150** and **55 × 25 × 150**

iv. Processing: Solve the equation by setup the material which is nanofluid and silicon and setup the boundary conditions which are inlet velocity, inlet temperature.

v. Post-processing: Simulation the model of microchannel and boundary flow will be done to get the data. In order to validate the CFD technique, the result is compared with (Qu & Mudawar, 2002). If the result not acceptable, then the simulation will be repeated will different parameter.

vi. The expected outcomes will be analyse consists of graphs and calculations.

vii. A complete report on this project will be written at the end of this projects.

The simplification of methodology are shown in the flowchart as **Figure 3.1**. It has been done from the beginning until finishing. This is to make sure that the work has been done smoothly by following the systematic and true path.

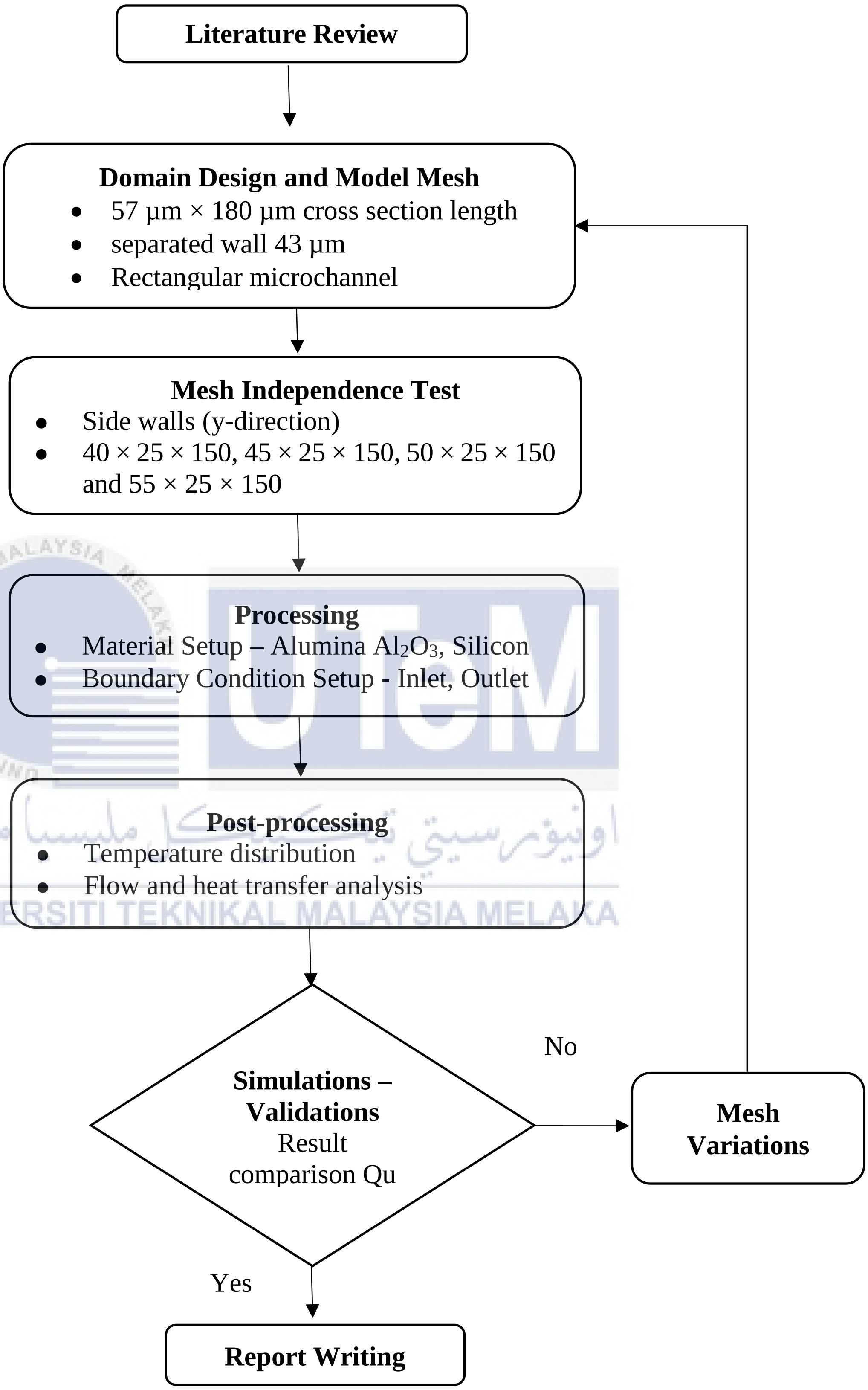


Figure 3. 1: Flow chart of the methodology

3.3 Domain Design

A schematic of the rectangular microchannel heat sink is shown in **Figure 3.2**. The microchannel heat sink characterise of high surface area per unit volume, large heat transfer coefficient and inventory of cooling fluid. Heat sink function as a heat exchanger. This heat sink transfers heat from an electronic component to a nanofluid. The heat sink area is 1cm^2 silicon wafer. This design and meshing is done by using GAMBIT software.

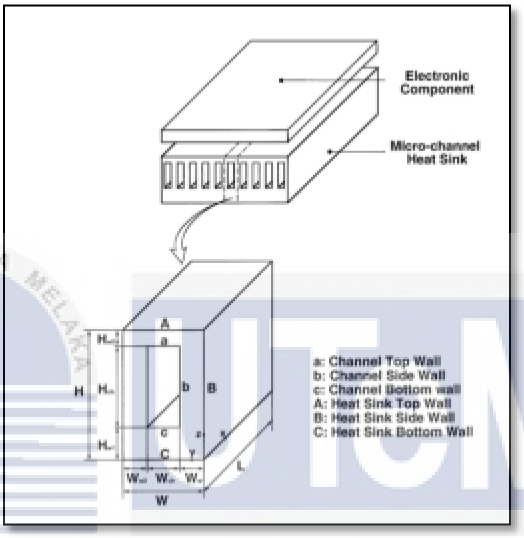


Figure 3. 2: Schematic of rectangular microchannel heat sink and unit cell [Qu & Mudawar, 2002]

Modelling the domain is started with the sketching the geometry of rectangular microchannel heat sink as shown in **Figure 3.3**. The channel dimensions has width of 57 µm, height of 180 µm and separated wall of 43 µm. The length of the model is 10mm. **Figure 3.3** shows the model of the rectangular microchannel. **Figure 3.4** shows schematic model of microchannel heat sink. **Table 3.1** shows the dimension for the unit cell of rectangular microchannel heat sink. The X -axis is the length of the channel, Y-axis is the height and Z-axis is the width of the channel.

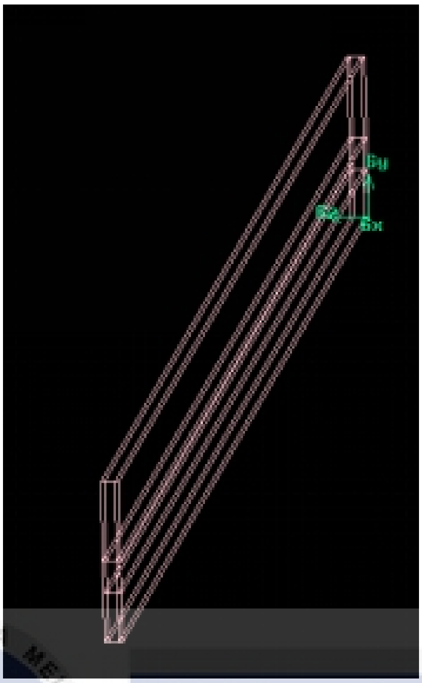


Figure 3. 3: Domain design

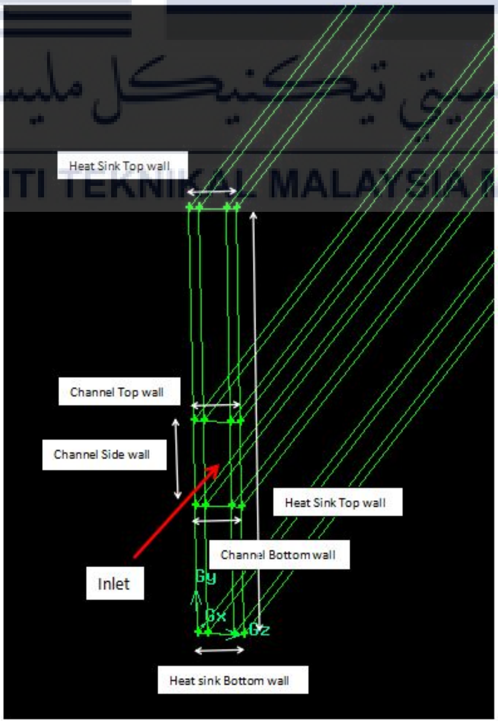


Figure 3. 4: Schematic model microchannel heat sink

Table 3. 1: Dimension for the unit cell of rectangular microchannel heat sink [Qu & Mudawar, 2002]

W_{w1} (μm)	W_{ch} (μm)	W_{w2} (μm)	H_{w1} (μm)	H_{ch} (μm)	H_{w2} (μm)	L (mm)
21.5	57	21.5	270	180	450	10

A rectangular heat sink model is developed to analyse nanofluid flow by applying velocity flow at the inlet and outlet. **Figure 3.5** shows the direction of the velocity inlet and velocity outlet. The velocity of the nanofluid flows are to be determined based on a given geometry. But, for the pressure gauge are fixed to zero value due to conditions are at an atmospheric pressure. Near the channel wall, no slip condition is applied.

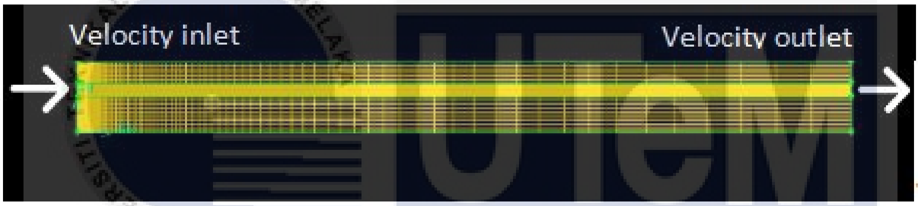


Figure 3. 5: Flowing Velocity inlet and outlet

3.4 Model Meshing

Meshing plays the important role in the simulations process. In the accuracy and stability of the drawing, this meshing is most significant role. For our model drawing which is rectangular microchannel, it's had been meshed using GAMBIT software. GAMBIT software is used for drawing the 3D objects. In this research, on the Quad map meshing and Hex map meshing have been used. Then, the file is imported to the Fluent for processing.

3.4.1 Quad map and Hex map

Quad map consist of the entirely quadrilateral and hexahedral element. Quad map and Hex map meshing are used for 3D drawing with a simple geometry model. It contains single and multi-block. **Figure 3.6** shows the isometric views of meshing geometry model**. Figure 3.7** shows the domain mesh of the model. The node at every surfaces at the inlet and outlet is determined with perfected. At the inlet side, the range of cell must be closer and lengthen toward for the outlet. This things are done to get the good results on the CFD simulations.

For 3D modelling, the files meshing of the modelling microchannel heat sink is transferred into Fluent. This is to determine fluid velocity with heat surface on the bottom that enclosed with the wall.

Figure 3. 6: Mesh Domain Isometric View

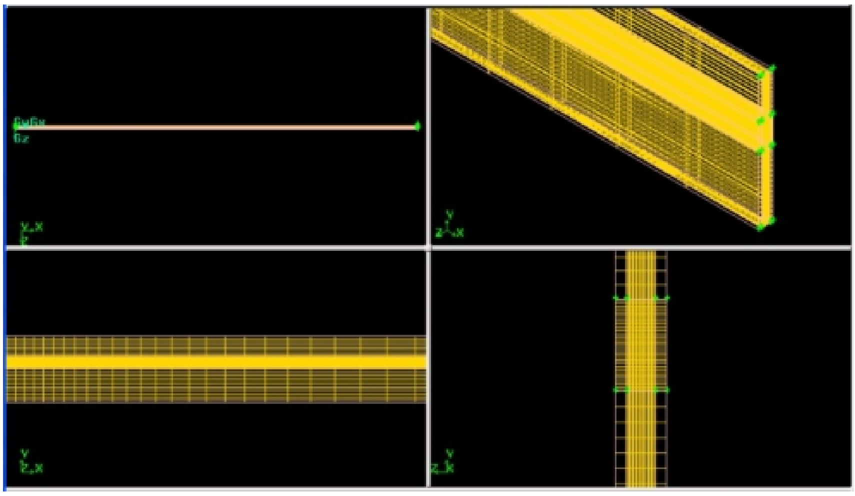


Figure 3. 7: Meshing Domain

3.5 Boundary Conditions

To perform the numerical analysis, the microchannel heat sink is developed. For this study, heat sink is made from silicon and the alumina, Al_2O_3 is the cooling fluid. A constant heat flux is provided by electric component on the top of the heat sink wall. In this boundary conditions, there are two zone-types specifications named boundary types and continuum types. Boundary types defined as the characteristics model of the internal and extenal boundary while continuum types is defined as the characteristics of the model within specified regions of its domain. **Table 3.2** shows the boundary types and **Table 3.3** shows the continuum types.

Table 3. 2: Boundary-type specifications

Name	**Zone type**
Inlet	Wall
Outlet	Wall
TopWall	Wall
SolidFluid	Interface

Table 3. 3: Continuum type specifications

Entity	**Zone type**
Alumina, Al_2O_3	Fluid
Silicon	Solid

In the hydraulic boundary conditions, the velocity is zero at all boundary except channel inlet and outlet. At channel inlet, a uniform velocity is applied.

$$u = \frac{Re.\mu_f}{d_h} \quad , \quad v = 0 \quad , \quad w = 0,$$

for $x = 0$, $H_{w1} \leq y \leq H_{w1} \leq H_{ch}$ and $W_{w1} \leq z \leq W_{w1} + W_{ch}$

At the wall, no slip condition is applied.

$$\frac{\partial u}{\partial x} = 0 \quad , \quad \frac{\partial v}{\partial x} = 0 \quad , \quad \frac{\partial w}{\partial x} = 0$$

for x = L, $H_{w1} \leq y \leq H_{w1} \leq H_{ch}$ and $W_{w1} \leq z \leq W_{w1} + W_{ch}$

At constant heat flux is applied on the top of the channel.

$$-k_s \frac{\partial T}{\partial z} = q'' \ , for\ 0 \leq x \leq L \qquad y = \text{H and } 0 \leq z \leq w,$$

The temperature for the liquid at the inlet channel constant.

$T = T_{in}$ for $x = 0$, $H_{w1} \leq y \leq H_{w1} \leq H_{ch}$ and $W_{w1} \leq z \leq W_{w1} + W_{ch}$

The average Nusselt number is defined as

$Nu = \dfrac{q''.d_h}{k_f (T_{\Gamma,m} - T_m)}$, where $T_{\Gamma,m}$ is the average temperature at the boundary,

Table 3. 4: parameter for fluid flow and heat transfer [Qu & Mudawar, 2002]

Re	**T_{in} (□C**	**q^n (W/m^2)**	**$k_{sillicon}$ (W/m. K)**
140.0	20.0	60.0	148

For the thermo-physical properties nanoparticles, nanofluid, silicon base fluid at 293.15K is shown in **Table 3.6**. The thermo-physical properties will assume as constant.

Table 3. 5: The Thermo-physical properties nanoparticles nanofluid, base fluid and silicon at 293.15K. [Mohammed, Gunnasegaran & Shuaib, 2010]

Properties (unit)	***p* (kg/m^3)**	**C_p (J/kg.K)**	**k (W/m.K)**	**µ (Ns/m^2)**
Nanofluid-water Al_2O_3	1027.92	4050.03	0.631	0.001028
Nanoparticles (Al_2O_3)	3970	765	40	-
Base Fluid(Water)	998.2	4182	0.613	0.001003
Silicon	2330	700	148	-

The numerical formula for the boundary layer thickness for the laminar and turbulence on a smooth plate.

Laminar: $$\frac{\delta}{x} = \frac{4.91}{\sqrt{\text{Re}}}$$

Turbulent: a) $$\frac{\delta}{x} \cong \frac{0.16}{(\text{Re})^{1/7}}$$, one-seventh-power law

b) $$\frac{\delta}{x} \cong \frac{0.38}{(\text{Re})^{1/5}}$$, one-seventh-power law combined with empirical data for turbulence flow through smooth plate.

In this study, the nanofluid which is alumina at 100nm nanoparticles and with concentrations 1% that are used as working fluid. The thermo-physical properties are listed as **Table 3.5** which is involved in the governing equation are calculated as the following equation.

Density:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p$$

Heat Capacity:

$$(\rho c_p)_{nf} = (1-\varphi)(\rho c_p)_{bf} + \varphi(\rho c_p)_p$$

Viscosity:

$$\mu_{nf} = \mu_{bf}\,(1 + 2.5\varphi)$$

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

The simulation analysis have been done for the rectangular microchannel heat sink using the fluent software and the results are shown in this section. The important fluid flow and parameter of the heat transfer that are using in this simulation are summarized. The first part is discuss about validation result between simulations and theoretical which is Qu Mudawar, 2002. Next, the meshing independence test results or grid independence test for the Nusselts number are plotted. Then, the heat transfer characteristics of the mirochannel heat sink and the boundary layer which are laminar and turbulent are calculated. Lastly, comparison of the Nusselt number between laminar and turbulent flow.

4.2 Validation result

This validation result is discuss about the comparison between simulation using fluent software and the theoretical based on Qu Mudawar, 2002 journal. This is to make the simulation result are valid. Based on the Qu Mudawar, 2002, the temperature gradient decreases from the channel inlet to the channel outlet. The Reynolds number is set up for 140 for the validation. For the temperature distributions and wall fluxes are plotted in **Figure 4.1**. For the Nusselt number is calculated using the value of temperature distribution and wall fluxes and plotted in **Figure 4.2.**

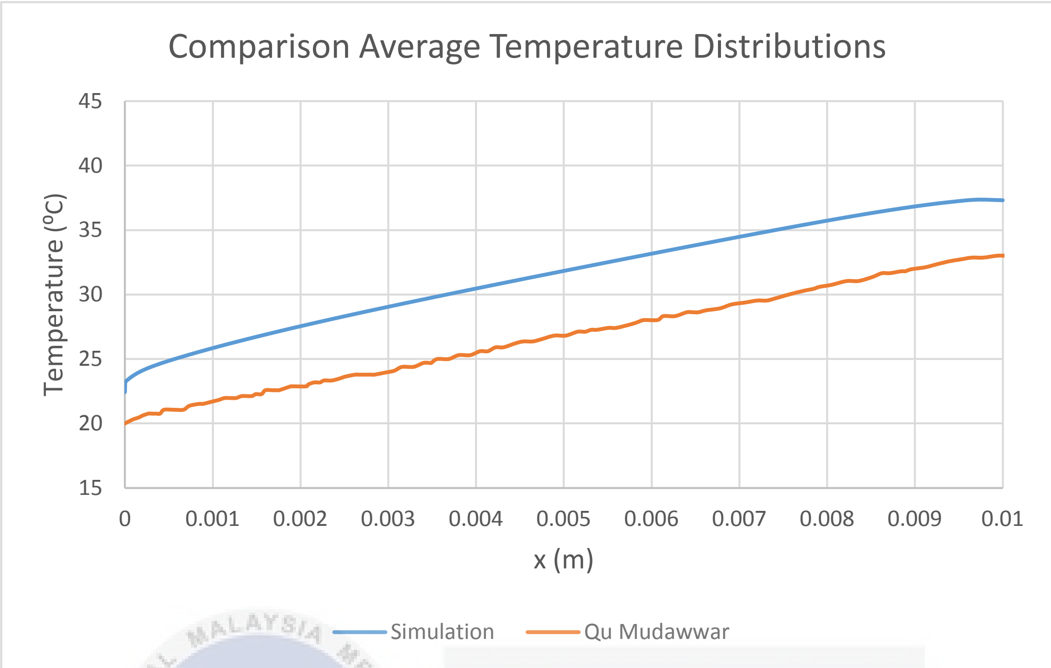


Figure 4. 1: Comparison of average temperature distribution

Figure 4.1 shows the comparison of averages temperature distribution between simulations results and Qu & Mudawar. From that, this simulations results are assume valid because have the same pattern with Qu Mudawar. Based on Qu & Mudawar (2002), the average temperature distributions lower at the inlet and increase linearly across the microchannel heat sink. From that **Figure 4.1**, there are small error between simulations and theoretical. The difference between simulations and Qu & Mudawar around 2 ℃ along the channel. The percentage error is around 8.9%.

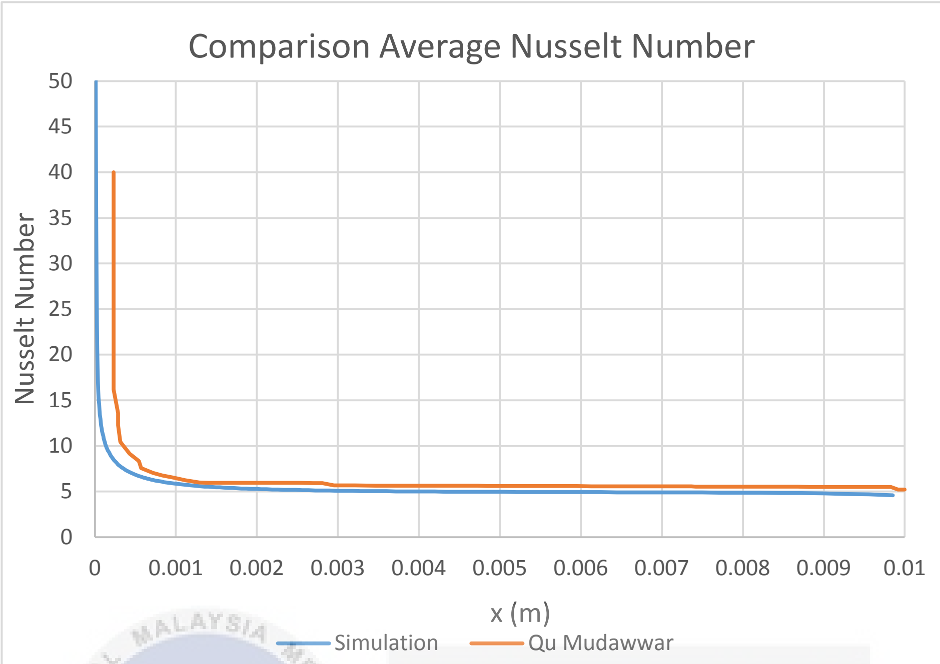


Figure 4. 2: Comparison of average Nusselt number

Nusselt number is calculated by using the following formula

$$Nu = \frac{q''(D_h)}{k_f(T_{\Gamma,m} - T_m)}$$

Where $T_{\Gamma,m}$ is the average temperature at the line side wall of the boundary

$$T_{\Gamma,m} = \frac{1}{\Gamma}\int T_{\Gamma}\,\partial\Gamma$$

and T_m is the fluid bulk temperature,

$$T_m = \frac{\int_{Ac} uT\,dA_c}{\int_{Ac} u\,dA_c}$$

The result shows that, the simulation result for the rectangular microchannel heat sink is similar from the Qu & Mudawar. Based on the Qu & Mudawar, the Nusselt number are large at inlet and decrease rapidly approximately to zero and constant value at the fully develop. This simulations are considered as valid because its shows the same pattern as the Qu & Mudawar. We can see that, there are small change between simulation and Qu & Mudawar. The percentage error of Nusselt number between simulations and Qu & Mudawar at the fully developed region is about 8.16%.

4.3 Mesh Independence Test

Mesh independence tests were analysed to establish the accuracy and consistencyof the fluent simulations. The simulations were run with laminar and standard turbulence. The simulations were run with constant Reynolds number 500 and velocity 5.7753m/s. This simulations study was performed with four different meshes size at the channel side wall which is y-direction of the fluid wall. The different meshes sizes are **40 × 25 × 150**, **45 x 25 × 150**, **50 × 25 × 150** and **55 x 25 × 150**. **Figure 4.3** shows the meshing independences test for isometric and front for the channel side wall. The Nusselt number are calculated for the laminar and turbulence and plotted as the following **Figure 4.4.** From that, we can all the line of the graph for laminar and turbulence are identically and there have no error. Even though the number of nodes this meshing is considered as the grid independences since the average Nusselt number is remain constants. By using the lower number of meshing, the results get are identically with the higher of mesh. So, there no need to performed simulations with the higher number of mesh. Therefore, this will reducing the computational efforts.

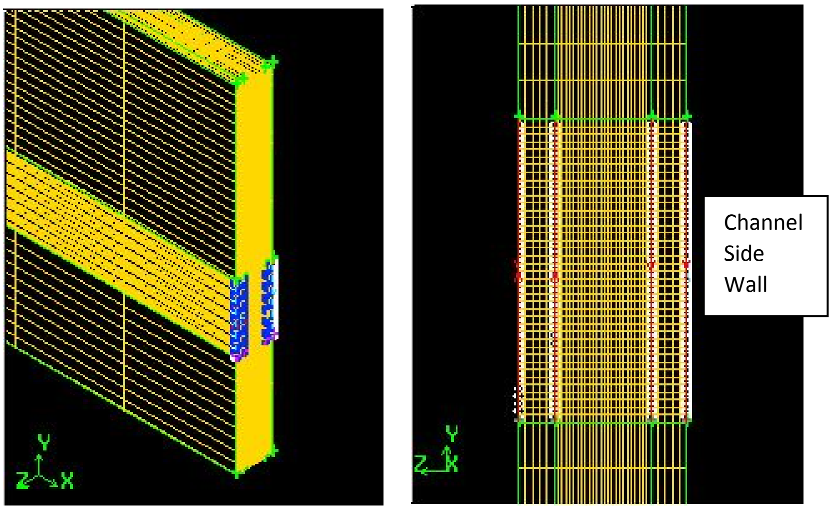


Figure 4. 3: Meshing Independence Test Isometric and front views microchannel.

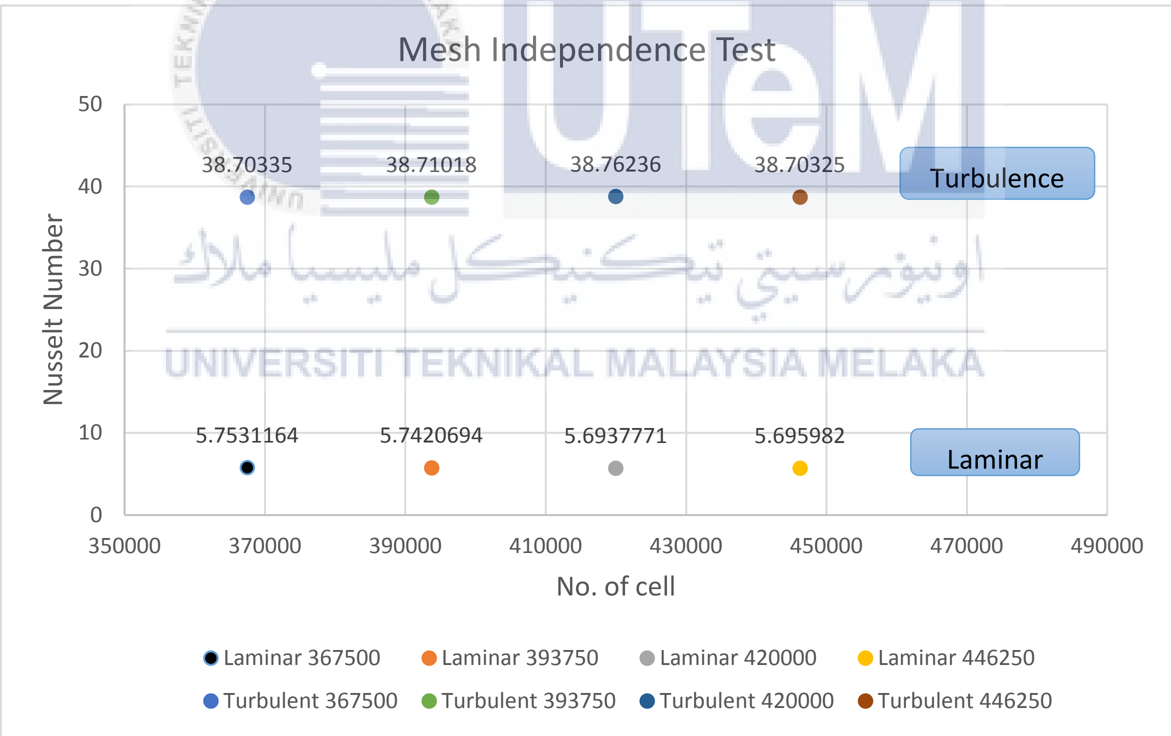


Figure 4. 4: Mesh Independence Test for Nusselt Number Laminar and turbulent

4.4 Local Temperature Distribution

Local temperature distributions shows the transfer of heat along rectangular microchanel. These are the flow of heat from inlet to outlet for the laminar and turbulent.

The temperature distributions along x-z planes are showing the transfer of heat for the plane top wall and plane bottom wall of the rectangular microchannel. **Figure 4.5(a-b)** show the contours for the heat transfer of the laminar and turbulence respectively. Based on that figures, the temperature gradient decreases from the inlet to the outlet due to the convection heat transfer which are the transfer of heat by the movement of nanofluid along the x-direction. This convections occurs because the nanofluid flow enclosed by the solid boundary which is silicon. The red colours refer to the hot temperature areas while the blue colours refer to the low temperature areas. The temperature increase from heat sink bottom wall to the heat sink top wall. The convection heat transfer for the laminar flow is smaller than the turbulent flow. This is because convection for laminar flow is slower than turbulence in the channel. The temperature gradient for laminar flow also smaller than the turbulence flow.

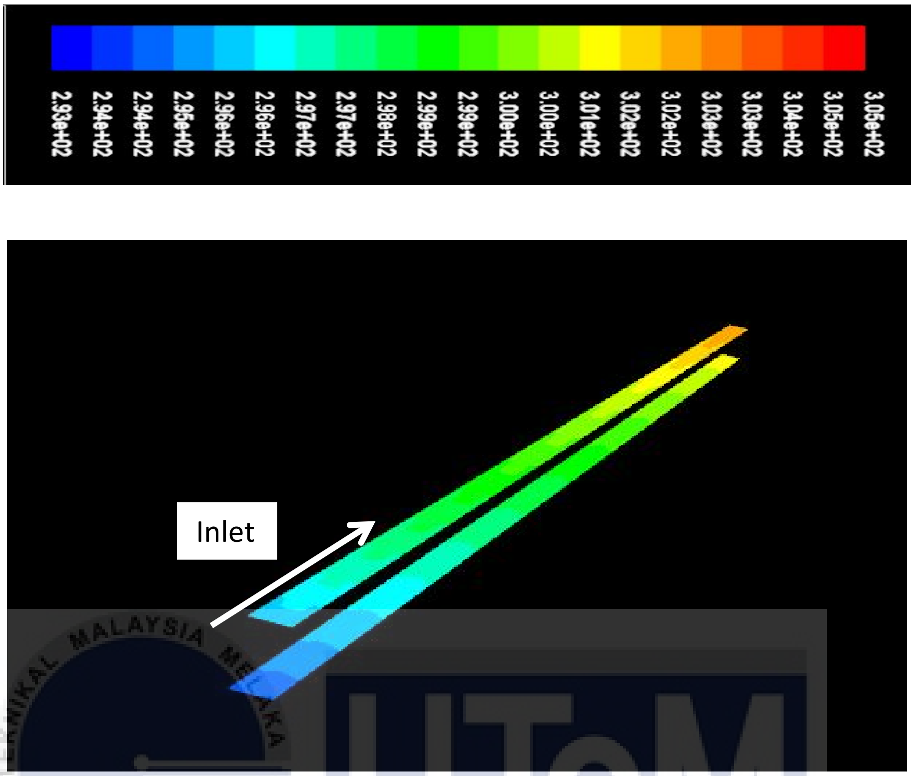


Figure 4. 5(a): Temperature Contours for plane top and bottom wall for laminar flow

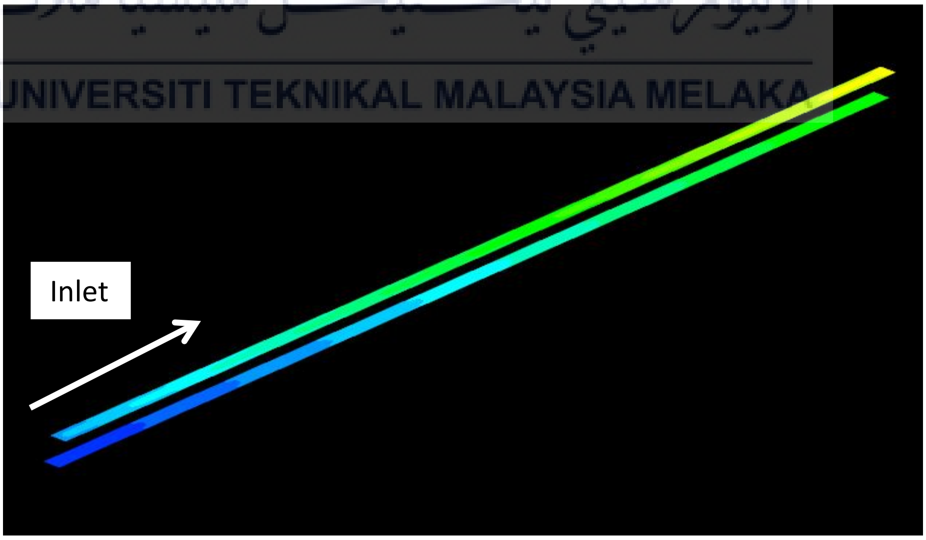


Figure 4.5(b): Temperature Contours for plane top and bottom wall for turbulence flow.

The temperature contours along the x-y planes are showing the transfer of heat for the heat sink middle plane at z = 0.05 mm and the heat sink side wall. **Figure 4.6(a-b)** show the contours for the heat transfer for the laminar flow. **Figure 4.7(a-b)** show the contours heat transfer for the turbulence flow. From the figures, the shape of the channel can see clearly. This is due to the larger differences for the temperature gradient between silicon and nanofluid. This also because silicon have higher thermal conductivity. As the higher the thermal conductivity of silicon, the temperature gradient of silicon is much smaller than the alumina nanofluid. However, the higher thermal conductivity will drive to the greater the heat transfer. This heat transfer much greater due to the large temperature differences.

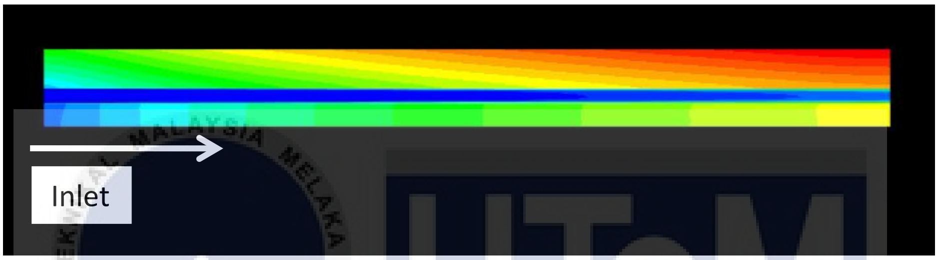


Figure 4. 6(a): Temperature contours for heat sink middle plane z = 0.05 for laminar flow.

Figure 4.6(b): Temperature contours for heat sink side wall for laminar flow.

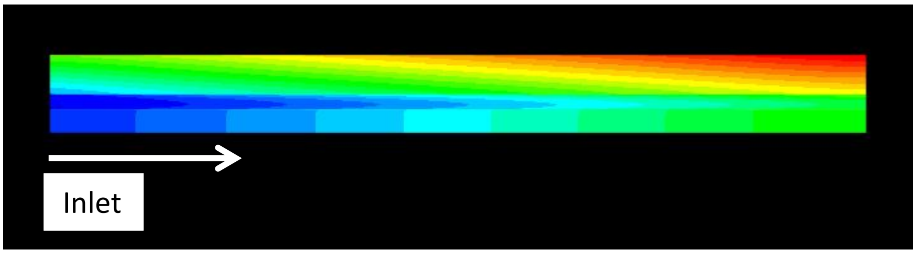


Figure 4. 7(a): Temperature contours for heat sink middle plane z = 0.05mm for turbulence flow.

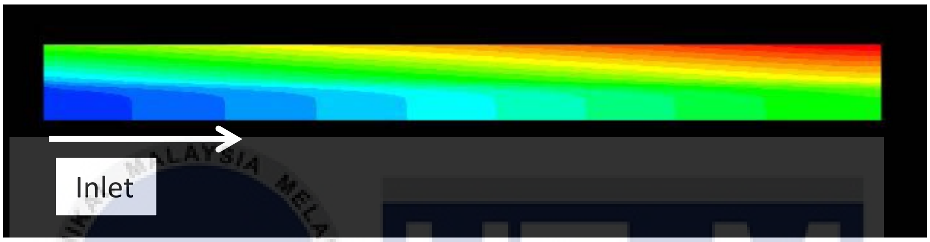
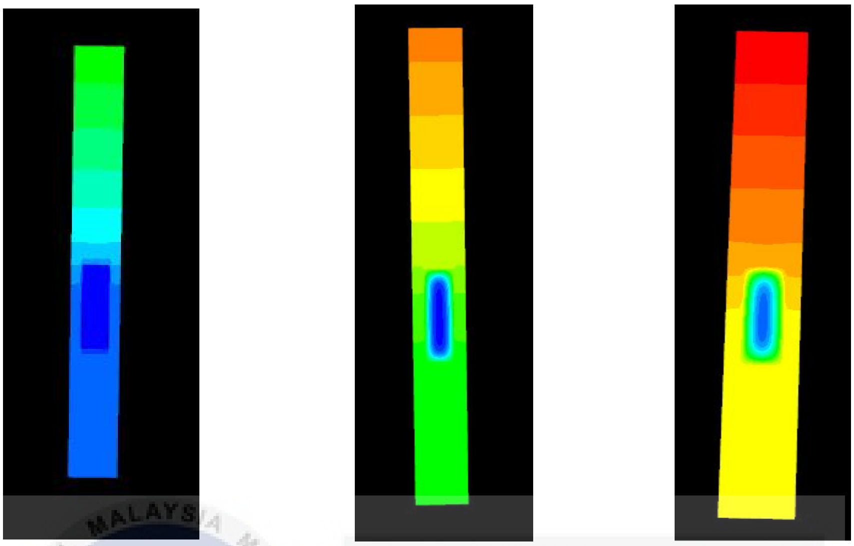


Figure 4.7(b): Temperature contours for heat sink side wall for turbulence flow.

The temperature contours along the y-z planes are showing the transfer of heat for heat sink inlet, heat sink middle and heat sink outlet for the x = 0, x = 5 mm and x =10mm respectively. **Figure 4.8(a-c)** show the contours heat transfer for the laminar flow. **Figure 4.9(a-c)** show the contours heat transfer for the turbulent flow. Based on the **Figure 4.8(a-c)** and **4.9(a-c)**, the variation temperature for the liquid is much bigger than the solid.

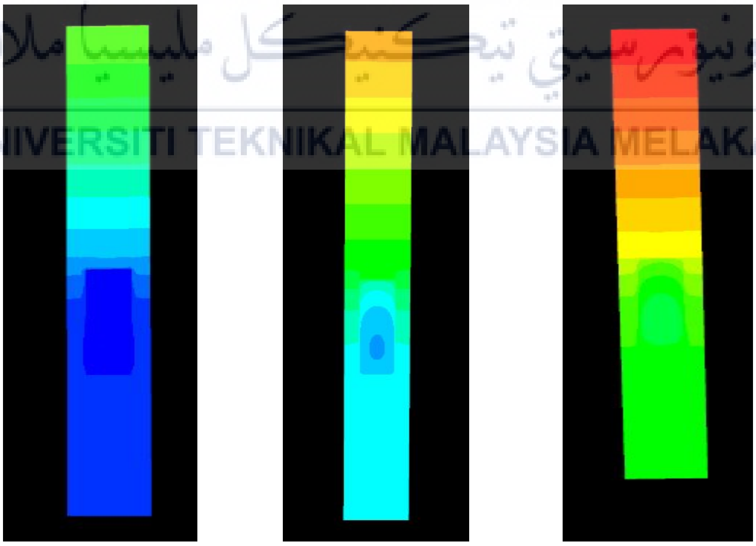
At the inlet (x = 0 mm) of the channel, the fluid temperature is uniform but due to the development of the thermal boundary layer, the temperature are changes. At the inlet (x = 0 mm), the temperature contour for laminar and turbulence are same and identically because thermal boundary layer doesn’t not occurs at this state. At the heat sink middle (x = 5 mm) and the heat sink outlet (x = 10mm), the thermal boundary layer have been occurs. For laminar flow, the temperature are higher compared to the turbulence flow. This is due to the laminar flow have higher heat flux compared to turbulence flow. As the present of the heat flux, means there are more quantity of heat entering the fluid particles. The heat flux of top wall are slightly larger compared to the bottom wall of nanofluid channel. Its can says that the heat transfer very effectively within the solid region from the top wall by conduction.

Due to the short distance between channel side wall and the high velocity gradient present, the heat flux at the side wall is higher than both top and bottom wall.



(a) x = 0 mm (b) x = 5mm (c) x = 10 mm

Figure 4. 8: Local temperature contours in y-z plane for laminar flow **(a)** heat sink inlet x = 0 mm **(b)** heat sink middle plane x = 5 mm **(c)** heat sink outlet x = 10 mm



(a) x = 0 mm (b) x = 5 mm (c) 10 mm

Figure 4. 9: Local temperature contours in y-z plane for turbulence flow **(a)** heat sink inlet x = 0 mm **(b)** heat sink middle plane x = 5 mm **(c)** heat sink outlet x = 10 mm

4.5 Flow and Heat Transfer Analysis

Flow and heat transfer analysis is to discuss about the fully developed flow in the entrance region for this microchannel. Hydrodynamic entrance region refers to the region in which the flow from the inlet to the point where the velocity profile is fully developed. Developing flow region are divided flow in into two regions, which are boundary layer region and irrotational (core) flow region. Boundary layer region is where viscous effects and velocity changes are important. Irrotational (core) flow region is where the frictional effects and velocity changes are negligible. Thermal entrance region in which the fully developed temperature profile become stable shape. The shape of the fully developed can be determined by the temperature and heat flux conditions along the channel. In this topic, the entry length and velocity profile fully for laminar and turbulence discussed in detail.

4.5.1 Comparison of Boundary Layer

Boundary layer is a layer in which viscous forces are important. When the fluid flow into the channel, the thickness of the boundary layer thickness gradually increase from zero until fill the entire channel. Hydrodynamic entrance region is a region for the channel inlet to the point where the velocity profile is fully developed. The length for that region is called hydrodynamic entry length, L_h. Hydrodynamic fully develop region is the region where the velocity profile fully developed and remain unchanged. The velocity profile in the fully develop for laminar and turbulent flow are different. **Figure 4.10(a-c)** show the velocity profile for the laminar and turbulence at the cross-section at y-z planes for the x = 1 mm, 5mm and 10mm respectively.

At x = 1mm for the laminar flow shown the developing of the velocity profile. At line x = 5mm and x = 10mm shown the fully developed velocity profile. At this region fully developed region, we called the hydrodynamically fully developed region in which where the velocity profile remain unchanged. At that region, velocity profile in fully developed in microchannel is parabolic for laminar flow. In fully developed for laminar flow, all the particles of the nanofluid moves at constant axial velocity along the streamlines of the channel. Thus, velocity profile is remains unchanged. For the radial directions, the velocity profile assume to be zero because there is no any motion in radial flow. Since, the viscosity and velocity profile are constant at fully developed region, there were transfer of momentum and energy and the wall shear stress will remains constant. So, the laminar flow much slower compared to turbulence flow.

However, at line x = 1mm, 5mm and 10mm, the velocity profile already fully developed for the turbulence flow. Since there is no changing of velocity profile at that region. We can see clearly at that region the velocity profile much fuller of flatter. In fully developed for turbulence flow, the effective shear stress of the turbulence are larger compared to laminar flow at the fully developed flow. This is due to the fluctuations nanofluid particles and mixing in the radial direction. The turbulence are characterise by eddies motions. These eddies motion are able to transfer the momentum and energy. So, this will leads to the faster for the turbulence flow. Then, the faster of flow, the faster the velocity profile to fully developed and remain unchanged as increasing the length of the channel.

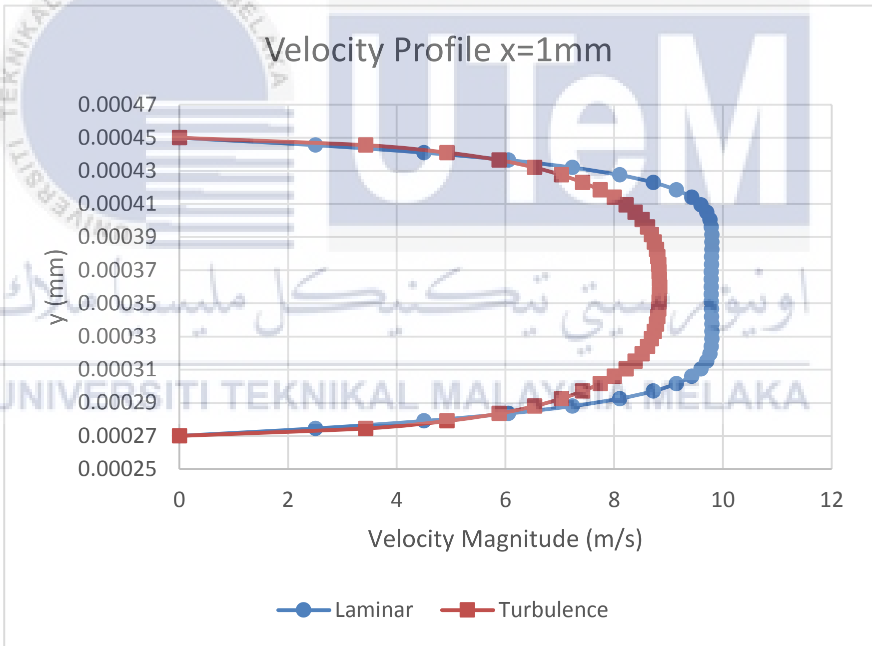


Figure 4. 10(a): Velocity profile for the laminar and turbulence flow at x = 0mm

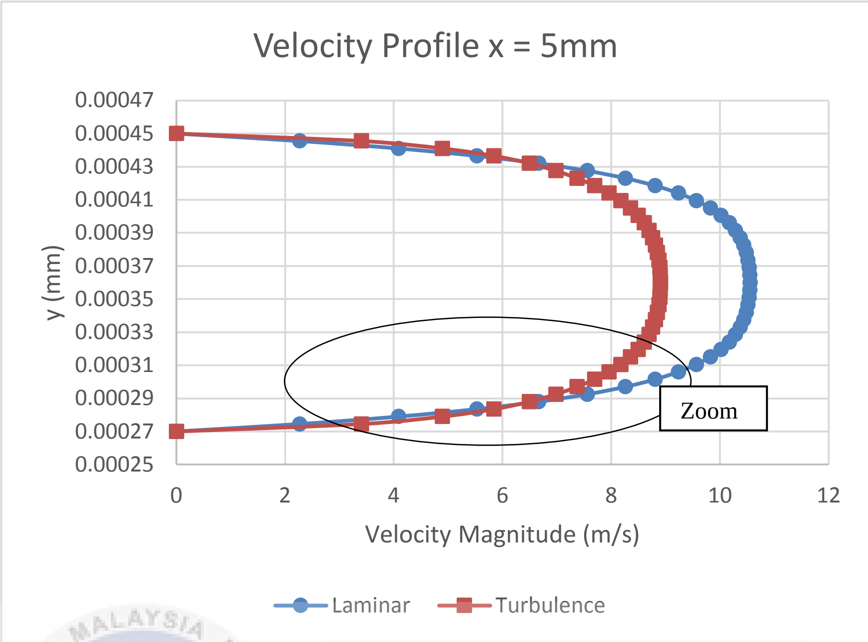


Figure 4.10(b): Velocity profile for the laminar and turbulence flow at x = 5mm

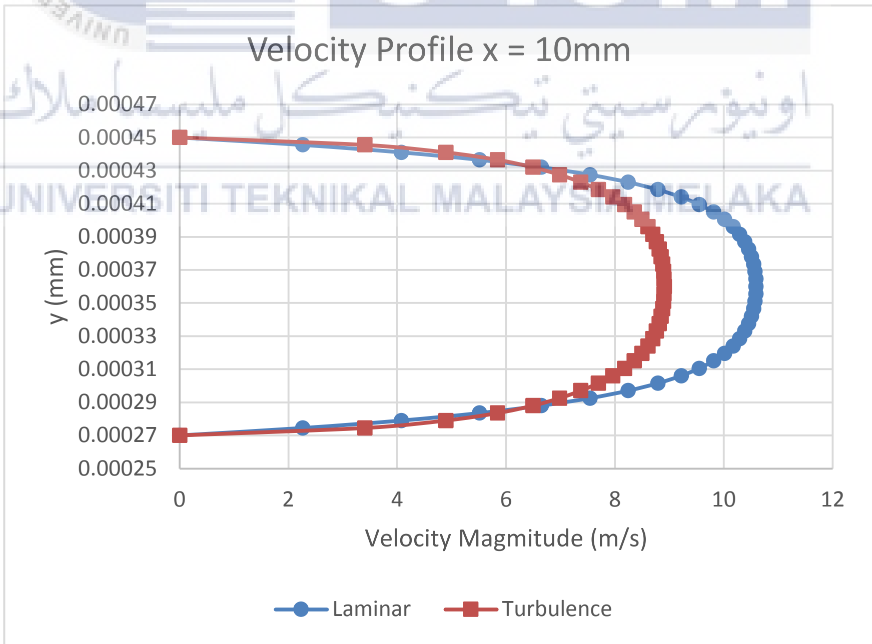


Figure 4.10(c): Velocity profile for the laminar and turbulence flow at x = 10mm

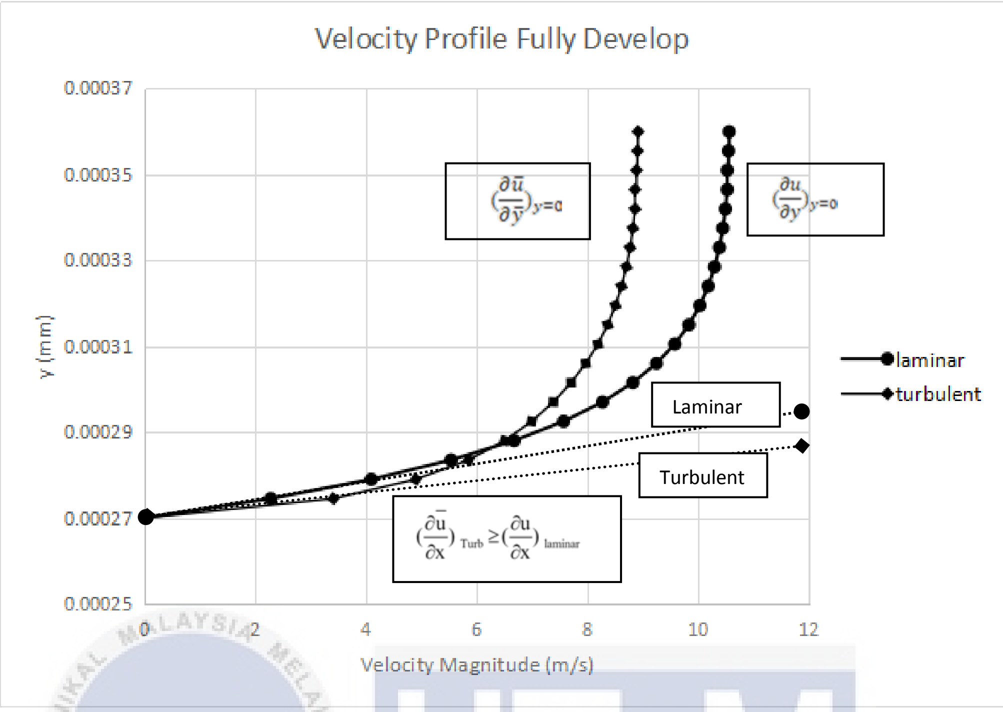


Figure 4. 11: The zooming of the velocity profile in fully developed for the laminar and turbulent at x = 5mm.

Figure 4.11 shows the zooming of the velocity profile and velocity gradient in fully developed for the laminar and turbulent. The wall shear stress for turbulence flow much bigger than laminar flow. So, the velocity gradient for turbulence much higher compared laminar. This is because of the turbulence flow early fully developed and remain unchanged as increasing the length of the channel.

4.5.2 Entry Region

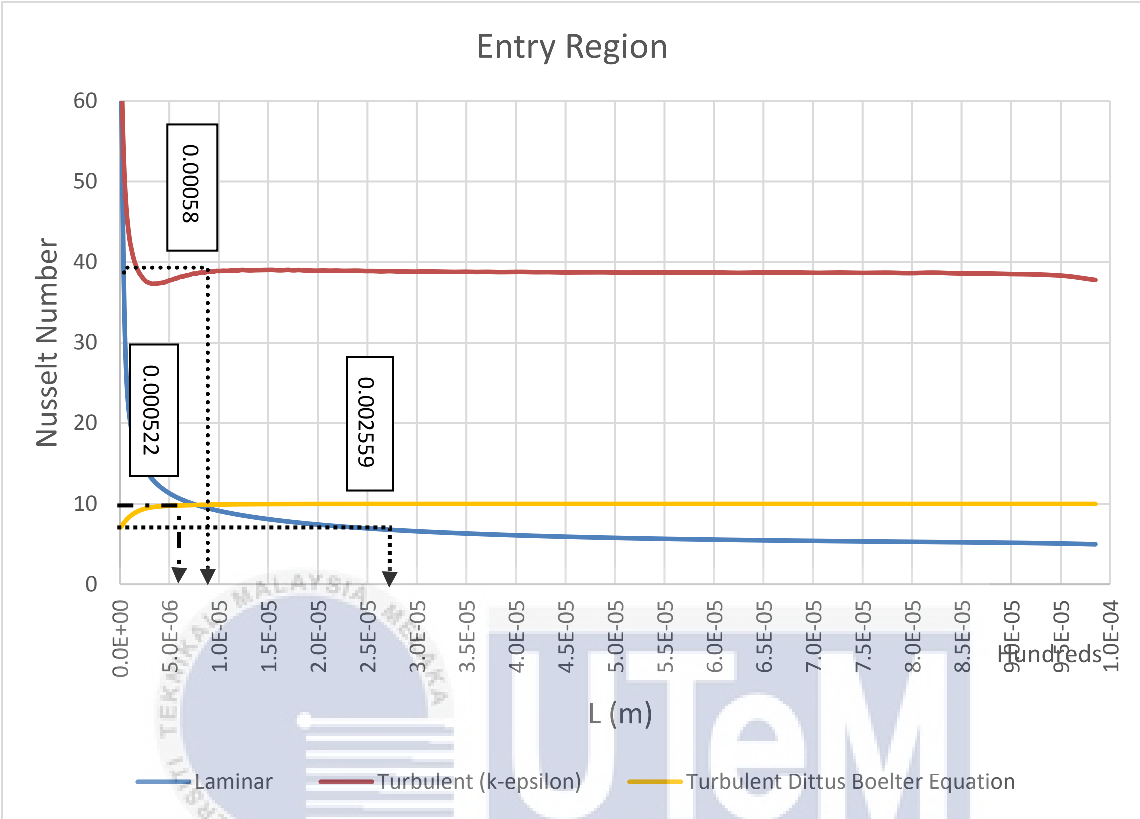


Figure 4. 12: Entry length laminar, turbulent (k-εpsilon) and turbulent (Dittus Boelter equation)

Figure 4.12 shows the entry region for the laminar and turbulence at fully developed. This is obtain when the velocity profile remain constant along the channel. From that figure, length region for the turbulence flow is much shorter compared to laminar flow. This is due to the turbulence flow achieved fully developed faster and remain constant compared to the laminar. The shorter the length of entry region, means the flow the flow is quite fast.

Based on the results and data that have from the simulations, the value entry regions for the laminar flow is 0.002559, turbulence (k-epsilon) flow is 0.000582 and turbulence (Dittus Boelter equation) is 0.000522. For the theoretical value are get from the equation as below for the laminar and turbulence flow. Then, the comparison have been made for the simulations and turbulence. **Table 4.1** shows the percentage error of entry region between the simulations and theoretical. From that table, we can see that the percentage error for laminar flow is high which is 18.23% compared to the turbulent (k-εpsilon) which is 4.6% and 6.18% for turbulent (Dittus Boelter equation).

$$L_{h,\,laminar} = 0.05 \times \mathrm{Re} \times D_h$$

$$= 0.0021645$$

$$L_{h,\,turbulent} = 1.359 \times \mathrm{Re}^{1/4} \times D_h \;, \qquad D \leq 10$$

$$= 0.0005564$$

Table 4. 1: The percentage error of entry region between the simulations and theoretical

	Entry Region, L_h		
	Present Work	**Theoretical value**	**Percentage Error**
Laminar (hD_h/k)	0.002559	0.0021645	18.23%
Turbulent (k-εpsilon) **(hD_h/k)**	0.000582	0.0005564	4.6%
Turbulent (Dittus Boelter equation) **($0.023*Re_D^{4/5}*Pr^n$)**	0.000522	0.0005564	6.18%

For the Nusselt number are calculated and plotted as the **Figure 4.12.** From that figure, we can see that the value of Nusselt number for laminar and turbulence flow. The results for laminar flow and turbulence are calculated by using equations below:

Laminar flow

$Nu = hD_h/k$

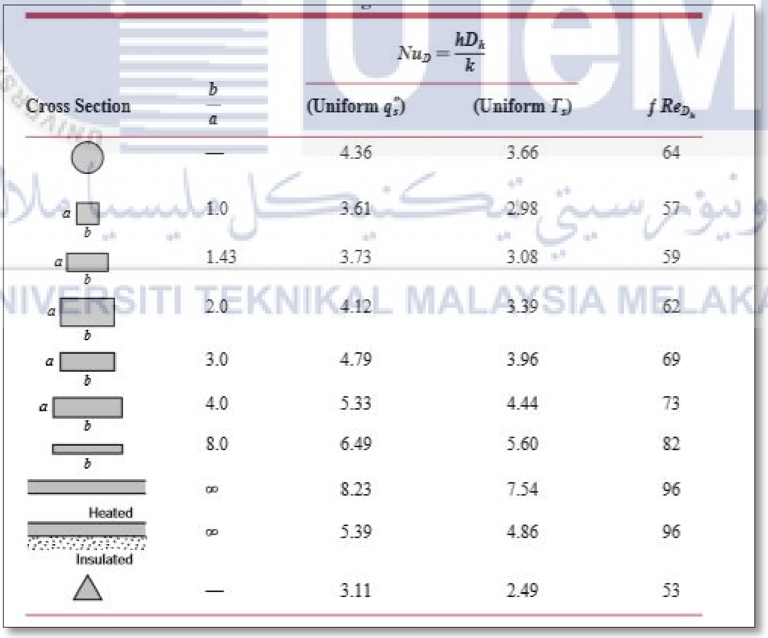
Turbulent flow (k-εpsilon)

$Nu = hD_h/k$

Turbulent (Dittus Boelter equation)

$Nu = 0.023 \times Re_D^{4/5} \times Pr^n$,   where $Pr = \frac{C_p \mu}{k}$, $60 \leq Pr \leq 160$,   n = 0.4 fluid being heating

Table 4. 2: Nusselt numbers and friction factors for fully developed laminar flow in tubes of differing cross section [Lavine, A. S. 2007)]



Cross Section	$\frac{b}{a}$	$Nu_D = \frac{hD_h}{k}$ (Uniform q_s'')	(Uniform T_s)	$f Re_{D_h}$
(circle)	—	4.36	3.66	64
a, b	1.0	3.61	2.98	57
a, b	1.43	3.73	3.08	59
a, b	2.0	4.12	3.39	62
a, b	3.0	4.79	3.96	69
a, b	4.0	5.33	4.44	73
b	8.0	6.49	5.60	82
	∞	8.23	7.54	96
Heated / Insulated	∞	5.39	4.86	96
(triangle)	—	3.11	2.49	53

For the theoretical value of the laminar flow are calculated based on the **Table 4.2** which is for uniform heat flux. **Table 4.2** shows the Nusselt numbers and friction factors for fully developed laminar flow in tubes of differing cross section. The calculations are based on the cross sections of the channel which is ratio of the width and length. From that, the ratio is 3.1579 and make interpolation between 3.0 and 4.0 for the uniform heat flux. So the value for Nusselt number that get based on that table is 4.8753. Based on results above, the percentage deviation are calculated based on comparison between laminar and turbulence flow. For laminar flow, the percentage deviation is 146.77%. For the turbulence, the percentage deviation between Turbulent (k-εpsilon) and Turbulent (Dittus Boelter equation) is 28.75%. From the results of Nusselt number, we can conclude that this study is turbulence flow since there is small of percentage deviation between simulations and theoretical.

Table 4. 3: Comparison Average Nusselt number between Laminar and Turbulence flow.

Nusselt Number				
Present Work		**Theoretical Value**		**Percentage Deviation**
Laminar (hD_h/k)	6.8990	**Laminar** (from **Table 4.2) [**Lavine, A. S. 2007]	4.8753	146.77%
Turbulent (k-εpsilon) **(hD_h/k)**	38.0124	**Turbulent** (Dittus Boelter equation) **($0.023*Re_D^{4/5}*Pr^n$)**	9.9797	28.75%

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In this research entitled "Comparison of Laminar and Turbulent Model of Nanofluid Flow in Microchannel" is performed by the simulations for nanofluid flow which is alumina, Al_2O_3 through the rectangular silicon microchannel by using the laminar and k-εpsilon model. The thermal and hydrodynamic characteristics of microchannel are studied. The fluid flow and heat transfer were analysed based on the simulations. The temperature distributions flow at solid and liquid region can be approximately as linear. The highest temperature is located at the channel top wall near the wall outlet for laminar and turbulence. The temperature gradient of silicon is much smaller than the alumina nanofluid. For laminar flow, the temperature are higher compared to the turbulence flow. This is due to the laminar flow have higher heat flux compared to turbulence flow. As the present of the heat flux, means there are more quantity of heat entering the fluid particles. The heat flux of top wall are slightly larger compared to the bottom wall of nanofluid channel.

The entrance length and velocity profile were obtained and investigated. The velocity profile fully developed for laminar flow is parabolic while turbulence flow is flatter or fuller. Turbulence flow much faster to fully develop compared to laminar flow. Increasing Reynolds number will increase the length of fully developed. The velocity gradient at fully developed for turbulence flow much higher compared to turbulence flow. For the thickness, turbulence flow much thicker than the laminar flow at same Reynolds number.

The detailed of the average Nusselt number was discussed in detail. The entry region for laminar and turbulence are calculated. The percentage error between simulations for laminar flow is 18.23%. For turbulence flow k-epsilon and Dittus Boelter equation are 4.6% and 6.18% respectively. The percentage deviation for the laminar flow between simulations and theoretical about 146.77%. The percentage deviation for the turbulence (k-epsilon) and turbulence (Dittus Boelter equation) is 28.75%. We can assume that the flow is turbulence since the percentage deviation for laminar is smaller than turbulence at Reynolds number 500.

In this study, a general concepts an effects of nanoluid on the rectangular microchannel heat sink had been studied base on laminar and turbulence flow. As a results there are a lot of possible future work can be conducted by referring to this research project as a base of initiate. In future, in order to future study for the effects of nanofluid, there are few ways that can be undertaken such as:

1) Conduct a simulations with RANS turbulence model, k- ω (Standard, BSL, and SST).
2) Conduct an experiment by undertaking the same boundary and simulations conducted and stated in this study.
3) Conduct a simulations by using the difference of concentrations of nanofluids.
4) Conducts a simulations with difference length and shape of channel

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