HEAT TRANSFER IN STAGGERED OBLIQUE FIN MICROCHANNELS

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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This thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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ABSTRAK

Proses penambahbaikan prestasi pemindahan haba di dalam sinki haba saluran mikro masih boleh dipertingkat lagi untuk mengawal pembaziran haba yang meningkat daripada komponen elektronik. Serupa dengan sirip serong, sirip serong tidak tersusun juga mempunyai aliran sekunder yang membatu membaiki campuran cecair untuk meningkatkan pemindahan haba. Walau bagaimanapun, sirip serong tidak tersusun mempunyai lebih banyak pecahan disebabkan susunan sirip yang tidak teratur yang mengelokkan proses penukaran aliran menyebabkan ia sering berada dalam keadaan membangun. Penukaran aliran ini mempengaruhi ketebalan lapisan sempadan terma untuk berkurang dan menambah kejatuhan tekanan lantas meningkatkan pestasi pemindahan haba. Oleh itu, dua buah model sirip serong tidak tersusun yang berbeza dari segi posisi ketinggian ketidak susunan dimodelkan bagi memodulasi aliran di dalam sinki haba saluran mikro. Persamaan momentum navier-stokes, persamaan kesinambungan dan persamaan tenaga telah diselesaikan oleh ANSYS FLUENT 18.1. Fluks haba, 65 W/cm^2 dan kelajuan masuk adalah tetap. Kejatuhan tekanan dan perbezaan suhu keluar dan masuk aliran pada kedua-dua model sirip serong tidak tersusun adalah lagi tinggi berbanding dengan sirip serong. Pengubahsuaian yang dicadangkan telah terbukti sebagai salah satu cara untuk menambahbaik prestasi pemindahan haba di dalam sinki haba saluran mikro.

ABSTRACT

Enhancement of the heat transfer performance in microchannel heat sink to handle the increased dissipation of heat from electronic components is continuously improved. Similar with oblique fin, staggered oblique fin also provides a secondary flow which improved the fluid mixing which enhance heat transfer. However, staggered oblique fin has much more breakage due to the staggered designs that improved the regeneration of the flow causing it to always be in developing state. This re-initialization of the flow effecting the thickness of the thermal boundary layer to be reduced and increasing the pressure drop thus resulting a better heat transfer performance. Therefore, two models of staggered oblique fins which differs in the height of staggered positions are modelled in order to modulate the flow in microchannel heat sinks. The Navier-Stokes momentum equation, continuity equation an energy equation are solved simultaneously by ANSYS FLUENT 18.1. Heat flux of 65 W/cm^2 and inlet velocity is fixed. The pressure drop and temperature difference of the outlet and inlet of the flow in both of the staggered oblique fins are higher compared to the oblique fins. The proposed modification is found to be one of the effective ways to enhance the heat transfer performance in microchannel heat sink.

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LIST OF ABBREVIATIONS

MCHS	**M**icro **C**hannel **H**eat **S**ink

NOMENCLATURES

Nu	Nusselt number
Re	Reynolds number
T	Temperature
c_p	Specific heat capacity, J/kgK
dp	Pressure drop, Pa
q	Heat transfer rate, W
θ	Oblique angel, deg
ρ	Mass density, kg/m^3
$_{ave}$	Average
$_{in}$	Inlet
$_{\mathrm{out}}$	Outlet

CHAPTER 1

INTRODUCTION

1.1 Background

Electric components release heat and need to be transferred to the surrounding during their operation. They shows the tendency for smaller, faster and denser chips with higher transfer rate and makes the thermal management becomes more complicated. Eventually, the heat sink will stop working if there is no efficient way to distribute the heat dissipated and control the temperature increment. Therefore, enhancements are needed to be applied on the heat sink performance.

Due to a higher demand of superior cooling of many devices or applications the heat transfer enhancement, various studies have been performed. Various type of enhancements were studied and they can be classified into three broad categories; passive, active and compound techniques. However, passive techniques is the most preferable by the researchers as it is simple and applicable. The most favourable passive techniques is by using fins in the microchannel. A fin is a surface that protrude from the surface. This increase the surface area of the fin in contact with the fluid flowing, thereby increasing the heat convection. [1]

Tuckerman and Peace [2] was the first to introduce the idea of microchannel heat sink (MCHS) in 1981. The silicon MCHS has a very small volume and can achieve a heat flux of 7.9×10^6 W/m^2 with the maximum temperature difference of 71 °C between the substrate and the inlet water. However, this MCHS has high pressure drop. Secondary flow is known for promoting better fluid mixing and enhance the rate of heat transfer in the microchannel. Hence, secondary flow can be promoted in the MCHS. This can be observed in the work by Raja Kuppusamy [3] where slanted passages were introduced along the channel wall between the adjacent channels in alternating orientation.

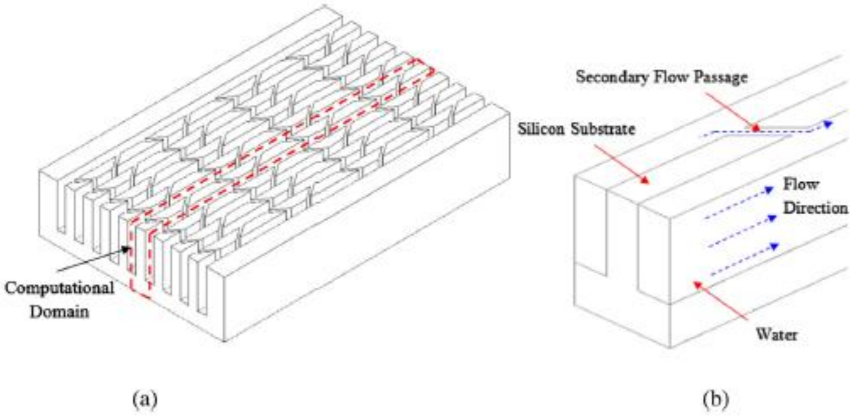


Figure 1.1: (a) MCHS with alternating slanted secondary passage (b) Detailed view of the computational domain where the fluid flows in the main channel and the secondary flow. [3]

Other than this proposed design of the fin many researchers has developed improved designs for the fin such as oblique fin, for example Subramanian and Sridhar [4] propose variants of microchannel geometries to investigate the performance enhancement by modifying the oblique fin.

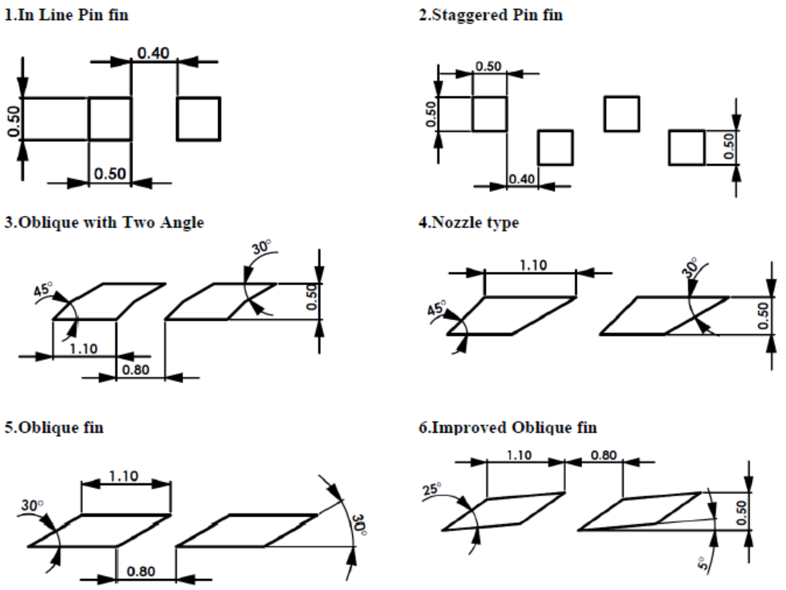


Figure 1.2: Microchannel fin geometries with specific dimensional details [4]

Subramanian and Sridhar [4] concluded that the staggered pin fin geometry is the best choice and is able to perform better in the thermal performance as the only criteria irrespective to the pumping power. This paper is the continuation of that. In this present study, a staggered oblique fin with slanted passage will be design, simulate and validate. The pressure drop and the thermal boundary layer are measured for various parameters to demonstrate the performance of the heat transfer.

1.2 Brief Overview

Heat transfer enhancement technique used to increase the rate of heat transfer without affecting much the overall performance of the system significantly. Conventional oblique fin concept has been widely used to generate secondary flow in the conventional passage which enhance the heat transfer. The breakage of the conventional continuous fin into oblique sections lead to the re-initialization of the thermal boundary layer at the leading edge of each oblique fin thus reducing the thickness of the boundary layer. This regeneration of entrance effects causes the flow to always be in a developing state resulting in better heat transfer. Besides that, a small fraction of the flow will be diverted into adjacent main channel because of the existence of the smaller oblique fin. However, the wetted surface of the oblique channel is not being utilized effectively. This is due to the shock when the flow impinges the corner of the oblique fin that causing in an early separation from the surface.

The efficiency of the heat transfer in the passage may be low due to the designing and geometries of the oblique fin. Study had shown staggered fin gives good results with the overall performance if the pumping power is neglected. It behave excellently in the thermal performance. Therefore, a staggered oblique fin is proposed in this study to provide better heat transfer performance in MCHS. The performance of the simulation will be validate first by analysing the data with existing data. After validation process, staggered oblique fin simulation will take place.

1.3 Problem Statement

Among the topics discussed above, the conventional oblique fin has a lower heat transfer performance compared to the staggered pin fin. However, there are not much studies about the improvement of the staggered fin design. The present paper is to improve and compare the performance of the pumping power and the thermal boundary layer of a conventional oblique fin with a staggered oblique fin.

1.4 Objectives

The objectives in this study are:

1. To develop a model of staggered oblique fin.
2. To simulate and analyse the heat transfer performance of the modelled fin with existing data.
3. To investigate the influence of staggered oblique fin on the pressure drop and heat transfer performance.

1.5 Scope of Work

In order to design an effective fluid flow. This study involves only a single phase fluid flow:

- Newtonian fluid – Water
- Experimental study is excluded.
- This surface of the oblique fin is considered as constant fluid properties.
- Laminar flow.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Significant number of researchers are focusing on improving the heat transfer performance. Numerous studies on techniques to enhance heat transfer performance in conventional thermal application. Experimental techniques and simulation are mostly used to analyse heat transfer rate and secondary flow. An in-depth study of the literature published in this area is necessary to understand the approaches used to address the problem concerns

This chapter review the heat transfer performance in microchannel heat sink in previous study. The parameters and boundary conditions to simulate the performance of heat transfer also will be discussed in this chapter. Besides that, the improvement on the geometry of the microchannel that enhance the heat transfer performance also will be discussed.

2.2 Heat Transfer Performance

Reynolds number plays an important roles to enhance the heat transfer performance. Reynolds number is the ratio of inertial forces and is a parameter used to predict the flow condition whether it is laminar or turbulent. Kurtbas [5] concluded that the heat transfer performance is expected to increase if the heat transfer coefficient increase. The design proposed is to place fins inside a rectangular channel with some independent parameters which is Reynolds number was included. The paper investigated the concave and convex fin.

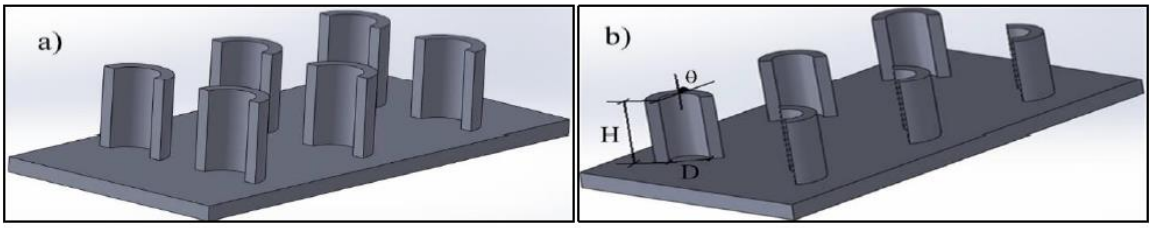


Figure 2.1: Schematic diagrams of fins (a) D=52 mm, H=8 cm, θ =90° (b) D=52 mm, H=8 cm, θ =45 [5]

Heat transfer is significantly dependent on Reynolds number. This is due to the increasing number of the friction coefficient for 1.1-34 times. Hence, the heat transfer increases 1.4-2.8 times compared to the smooth channel. The below graphs show that the higher the Reynolds number, the higher the friction coefficient will be.

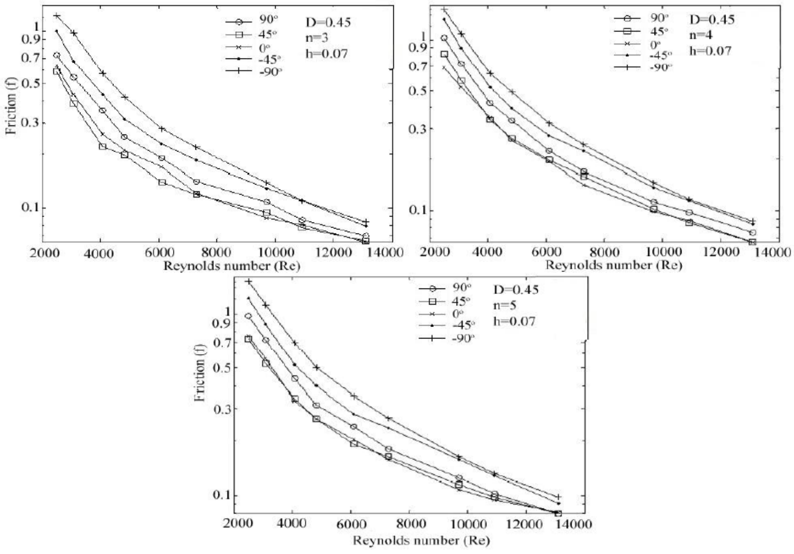


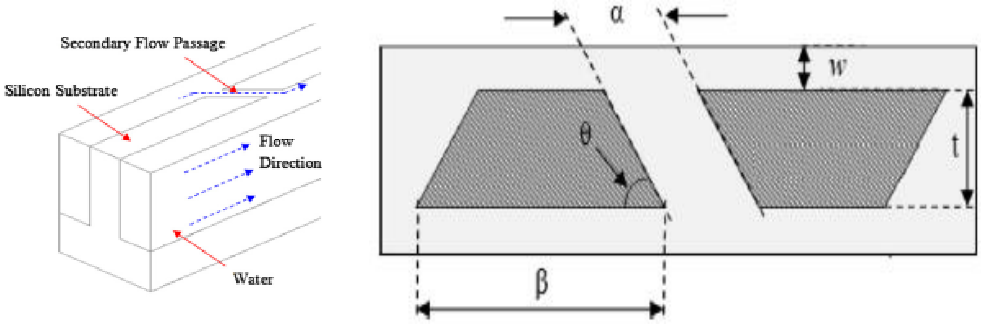
Figure 2.2: The effect of fin number coefficient for different fin angles [5]

Besides that, the wetted perimeter also important to enhance the heat transfer performance. According to S. Subramaniam [4] if the wetted surface area is smaller the thermal performance of the MCHS will become better. The paper compare between oblique fin and improved oblique fin according to their wetted surface area and the result shows that improved oblique fin is lesser than the oblique fin. However, improved oblique fin gives a higher thermal performance due to the accelerated secondary flow.

Increasing MCHS performance by using nanofluids as coolant was proposed by Reiyu [6]. It was proven that nanofluid-cooled MCHS could absorb more energy compared to water-cooled MCHS in a low flow rate. Besides that, results from experiment also shows a slight increase in the pressure drop due to the presence of nanoparticles in MCHS operation. The study on performance in MCHS using nanofluids were also carried out by Tu Chieh [7], numerically. Heat transfer enhancement can be obtained by adding nanoparticles to the coolant fluid that can change its thermos physical properties. Moreover, the paper suggest that by using fluids with lower dynamic viscosity and substrate materials with high thermal conductivity enhance the thermal performance of the MCHS. In terms of thermal resistance, the volume fraction and pumping power must be properly adjusted to get a lower value of resistance. Lower thermal resistance gives a higher heat transfer performance.

2.3 Secondary Flow: Oblique Fin

Oblique fin microchannel is attractive as it performs better than the conventional fin. The oblique cut on the fin reduces the boundary layer thickness thus regenerating the entrance that causes the flow to always be in a developing state [8]. This phenomenon improving the heat transfer performance in MCHS. Oblique fins increases the heat transfer coefficient by increasing the surface area to the volume ratio, as said by Malvia [1] compared to the conventional MCHS. Continuation of study on the MCHS that was first introduced by Tuckerman and Pease [2] to enhance a secondary flow. Raja Kuppusamy [3] introduced slanted passage in the channel wall between the adjacent channels in alternating orientation to generate a secondary flow. This model can cause disruption in the hydrodynamic boundary layer. The disruption able to decrease the thermal boundary layer thickness which automatically can improve the performance of the heat transfer. The overall performance increased by 146% when slanted passages were introduced and the thermal resistance reduce by 78% as calculated via numerical simulation.



(a) (b)

Figure 2.3: (a) Detailed view of the computational domain (b) Detailed view of the wall of the channel with its design variable.[3]

As an enhancement of the above study, a three-dimensional analysis were conducted by Ghani [9] for a wavy microchannel with oblique secondary channel in alternating orientation. The performance of the straight microchannel was compared to the wavy microchannel and it was proven that this improved model can increase the thermal performances up to 108%.

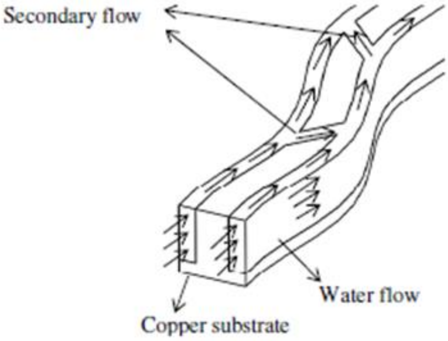


Figure 2.4: Schematic diagram of flow distributions in wavy microchannel [9]

According to Yan Fan [10], the averaged Nusselt number, Nu_{ave} increased up to 75.6% and the total thermal resistance decreased up to 59.1% for a cylindrical oblique fin MCHS compared to the conventional fin through both experimental and numerical approached.

2.4 Staggered Fin

Study shows that staggered fin can be considered as the best choice for a better thermal performance but lacks at the pumping power compared to the improved oblique fin as studied by Subramanian and Sridhar [4].

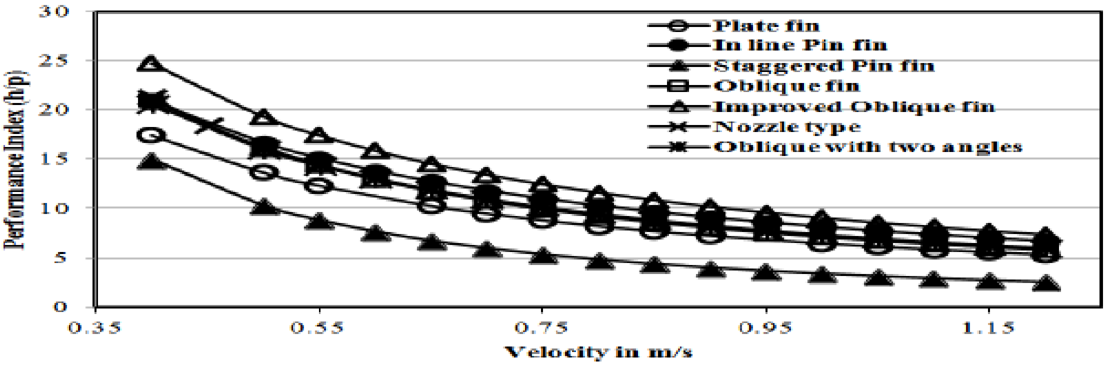


Figure 2.5: Comparison of performance index [4]

Based on the performance index, improved oblique fin shows the highest index which concludes that the higher thermal performance is achievable with a lesser pumping power.

A study was conducted to investigate the performance of heat transfer in heat sinks of microelectronic components by Nimesh [11]. Different geometries in tandem and staggered arrangements were analysed numerically on the heat sinks with uniform thickness. Concluding that the staggered heat sinks had a better performance over the standard ones. Furthermore, staggered fins with conic section provide enhanced quality factors at lower Reynolds number compared to the staggered fins with rounded leading edge.

2.5 Heat Transfer Enhancement Techniques

Various types of inserts were used in heat transfer enhancement devices and the most insert used was geometrical parameters [12]. The width, length, twist ratio, etc. can be an effective measures to increase the performance of heat transfer. Other than geometry, roughness also can give a better performance in case of flow with large Prandtl number and it can be developed by employing a corrugated surface which break and destabilize the thermal boundary layer.

CHAPTER 3

METHODOLOGY

3.1 Overview

The methodology applied consists of (i) validation of previous study on the heat transfer performance of a conventional microchannel; (ii) simulation on the oblique fin; (iii) modelling and simulating improved oblique fin which is staggered oblique fin with two different geometries (iv) determining the pressure drop for each type of simulation (v) analysing the temperature difference on the average outlet temperature and average inlet temperature of the fins. The temperature difference can be calculated by:

$$T_{diff} = T_{out,ave} - T_{in,ave}$$

The procedure of the study as shown in Figure 3.1. All the simulation was set into a laminar flow and used the same properties of coolant fluid. The temperature dependent materials properties of water as shown in Table 3.1. The simulation were generated by ANSYS FLUENT 18.1 for all of the simulation. The following assumptions were made in modelling the heat transferrin microchannel heat sink in the study to simplify the analysis: (1) steady-state (2) laminar flow (3) incompressible fluid (6) constant fluid properties (7) negligible radioactive and natural convective heat transfer from the microchannel heat sink.

Table 3.1: Properties of coolant fluid

Parameter	Properties
Density, ρ	1000 kg/m^3
Specific heat, Cp	4182 j/kg.K
Thermal conductivity	0.6 W/m.K
Viscosity	0.001 kg/m.s

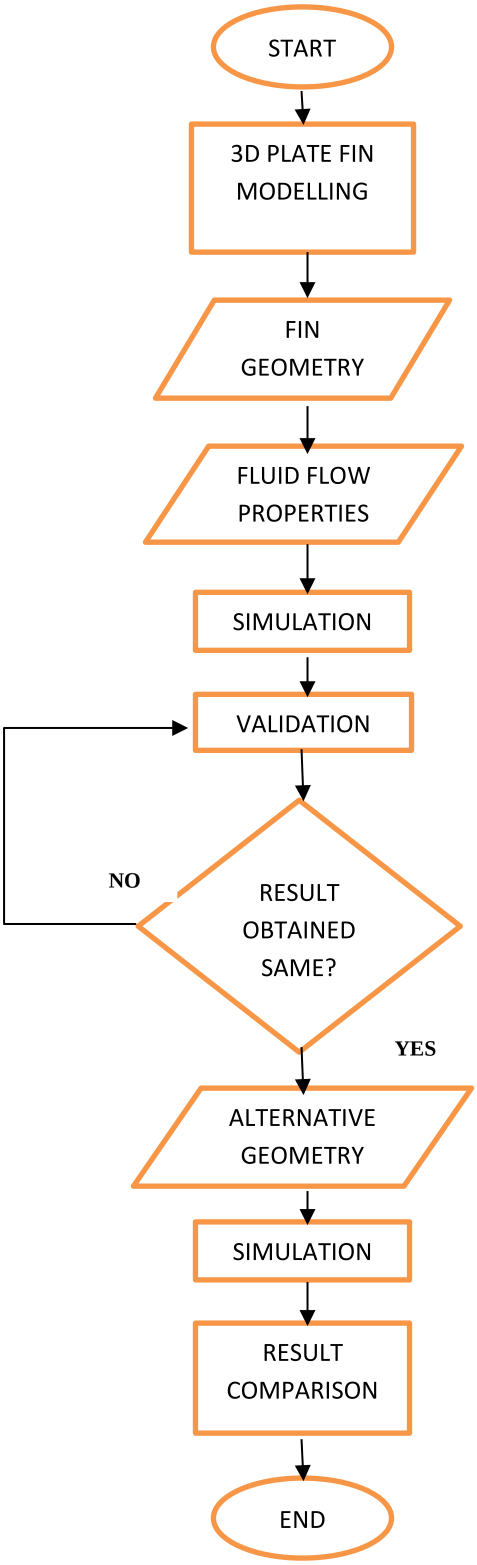


Figure 3.1: Flow chart of the research methodology.

3.2 Validation of Case Study

The plate fin microchannel has been selected for the validation purpose. The geometric details are chosen in the similar lies of the work carried out by Lee [8] which is considered as the reference data for validation. The dimensional details are shown in Table 3.2 and Figure 3.2. The computational analysis was carried out using ANSYS FLUENT 18.1 by varying the inlet velocity.

Table 3.2: Dimensional details used for validation

Parameter	Plate Fin
Size of heat sink	25mmX25mm
Main channel width (µm)	500
Fin width (µm)	500
Channel depth (µm)	1500
Hydraulic diameter (µm)	750
Heat sink material	Copper
Coolant fluid	Water

Fully developed velocity profile was assigned to the inlet. Periodic boundary was assigned to the sides. A uniform heat flux of 65 W/cm^2 was applied to the het sink surface at the bottom while the top of the microchannel heat sink is considered to be bonded with adiabatic cover. The flow of the coolant was set to be laminar. The inlet velocity ranged from 0.4 m/s to 1.07 m/s while the Reynolds Number ranged from 300 to 800.

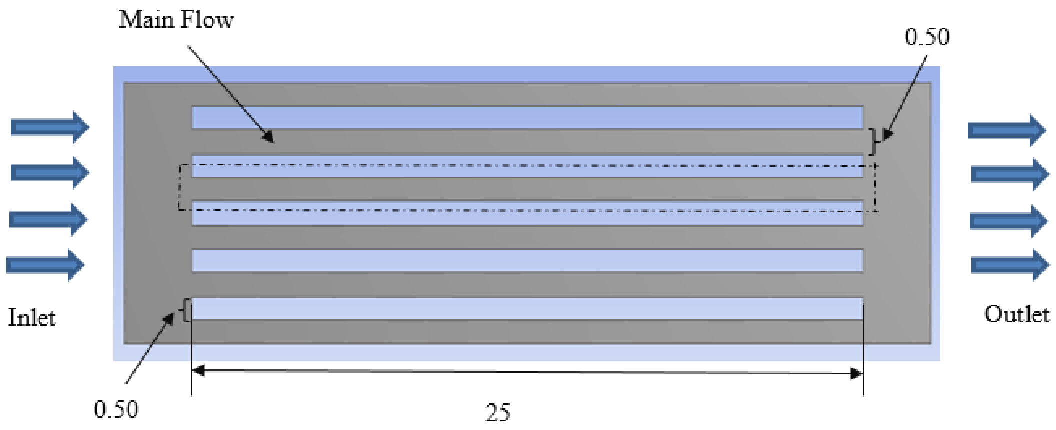


Figure 3.2: Plan view of plate fin microchannels with dimensions in mm

Only a pair of a fin and a channel has been chosen as the computational domain as the microchannel heat sink has periodically repeating fin and channel pairs and it was modelled in a 3-dimensional drawing in the DesignModeler ANSYS FLUENT. Then, the fin was meshed with uniform meshing. The meshed model was exported to FLUENT to proceed with the simulation process. The process of the simulation was based on the case study.

3.3 Oblique Fin Simulation

Oblique cuts were made along the fins to create a smaller, branching channels with the intentions to disrupt the thermal boundary layer development thus generating secondary flow as shown in Figure 3.3. Oblique fin microchannel was designed and the model adopted almost the same as the model proposed by Lee. The dimensional details as shown in Table 3.3 and Figure 3.4. Only a pair of fin-channel was simulated where the span-wise repeating channels were repeated only by the symmetry boundary conditions. The fin were modelled in DesignModeler and meshed with uniform meshing.

Upon exporting the mesh file to FLUENT, the 3D double precision pressure based on solver was selected with its standard SIMPLE algorithm and its pressure-velocity coupling method. A standard discretization scheme was used for the pressure equation while a second-order, upwind discretization scheme was selected both the momentum and energy equation. In this simulation, a full developed velocity profile was also applied to the inlets. In order to achieve the fully developed velocity profile in the inlets, first the outlet x-velocity and static temperature were exported from them FLUENT database. After that, the profiles were called to be read in the FLUENT database and applied at the inlet boundary condition. The pressure outlet boundary condition was assigned to the outlets, where the flow was assumed to reach atmospheric pressure at the outlet of microchannel. Symmetry boundary conditions was assigned to the sides that makes the shape of the microchannel turn into a herringbone pattern.

Table 3.3: Dimensional details for oblique fin microchannel

Parameter	Oblique Fin
Size of heat sink	25mmX25mm
Main channel width (µm)	500
Fin width (µm)	500
Channel depth (µm)	1500
Oblique channel width (µm)	300
Oblique fin length (µm)	1300
Oblique angle, θ (deg)	30
Hydraulic diameter (µm)	750
Heat sink material	Copper
Coolant fluid	Water

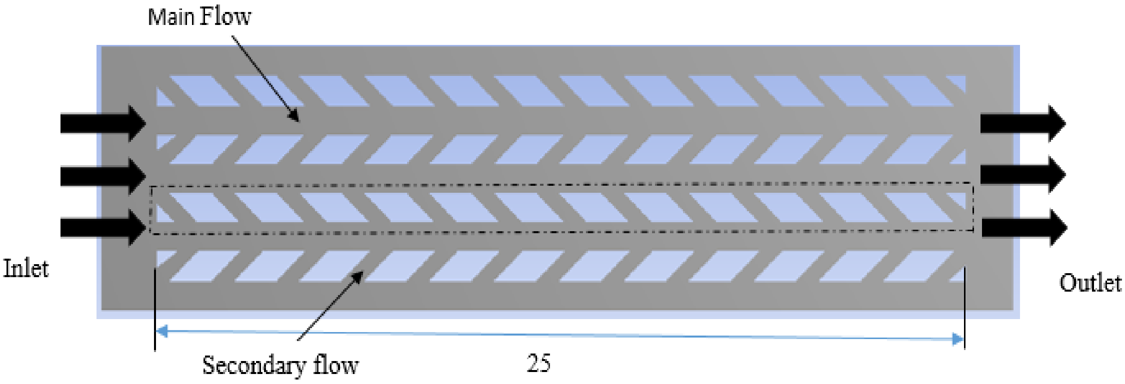


Figure 3.3: Plan view of oblique fin microchannels with dimension in mm

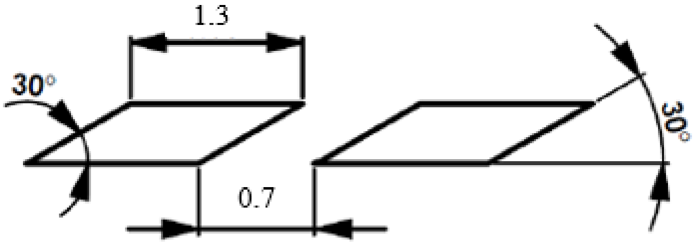


Figure 3.4: Oblique fin geometries with specific dimensional details in mm

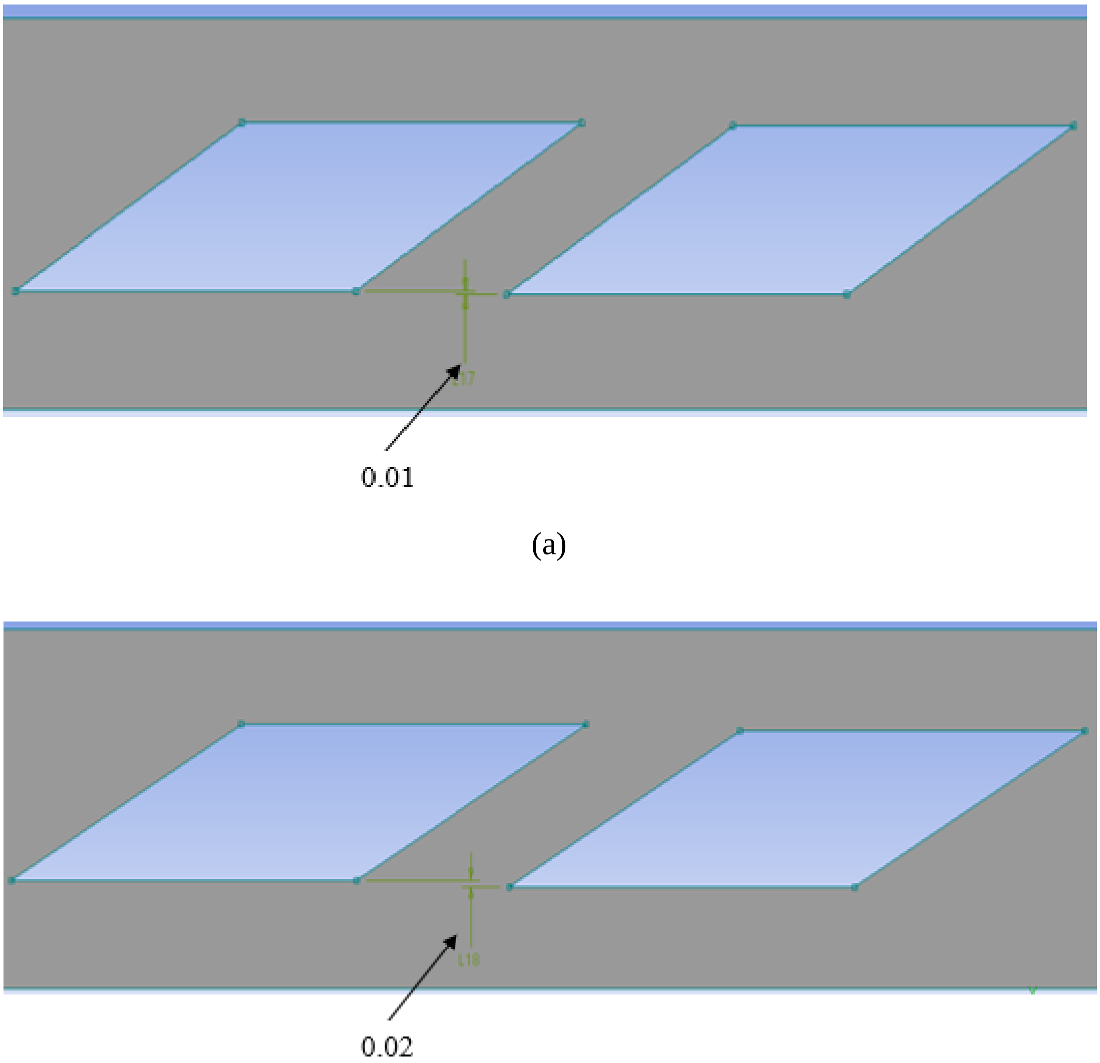
3.4 Staggered Oblique Fin

The current heat sinks design is an improved version of the oblique fin by adopting staggered position. Two model of staggered oblique fin microchannel were designed with different length of the oblique fin pitch. The difference between the first model and second model was about 10 µm. The dimensional details and geometries are shown in Table 3.4 and Figure 3.5.

Table 3.4: Dimensional details for staggered oblique fin microchannel

Parameter	1st Model	2nd Model
Size of heat sink	25mmX25mm	
Main channel width (µm)	500	500
Fin width (µm)	500	500
Channel depth (µm)	1500	1500

Oblique channel width (μm)	300	300
Oblique fin length (μm)	1300	1300
Oblique angle, θ (deg)	30	30
Height between the on oblique fin cut (μm)	10	20
Hydraulic diameter (μm)	750	750
Heat sink material	Copper	
Coolant fluid	Water	



(a)

(b)

Figure 3.5: Staggered oblique fin geometries (a) 1st model (b) 2nd model

The models were meshed uniformly and export to FLUENT and the simulation process was as the same as Oblique Fin simulation process. The sides of both of the staggered fin model was also assigned as symmetrical that made them also herringbone-like shape. The main flow and the secondary flow for both staggered fin were same as the conventional oblique fin.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the results for all the simulations done by using ANSYS FLUENT 18.1 on the heat transfer performance. The results consists of (i) validating the case study (ii) comparing the pressure drop across the fins (iii) determining the temperature difference in the outlet and inlet of the fins (iv) analysing the velocity and temperature profile along the fins and (v) analysing the grid independency test.

4.2 Validation

The pressure drop across MCHS for the simulation are presented in Figure 4.1, alongside the result from the case study which shows a good agreement. The highest and the lowest percentage difference between the simulation's results with the case study's results is 17.72% at Reynolds number 500 and 1.94% at Reynolds number 300 respectively. Meanwhile, Figure 4.2 shows the comparison of average Nusselt number between the simulation's result and case study's result. It shows that they only differs by 11.35%. The percentage difference of both results does not show a very big difference, thus making the validation acceptable.

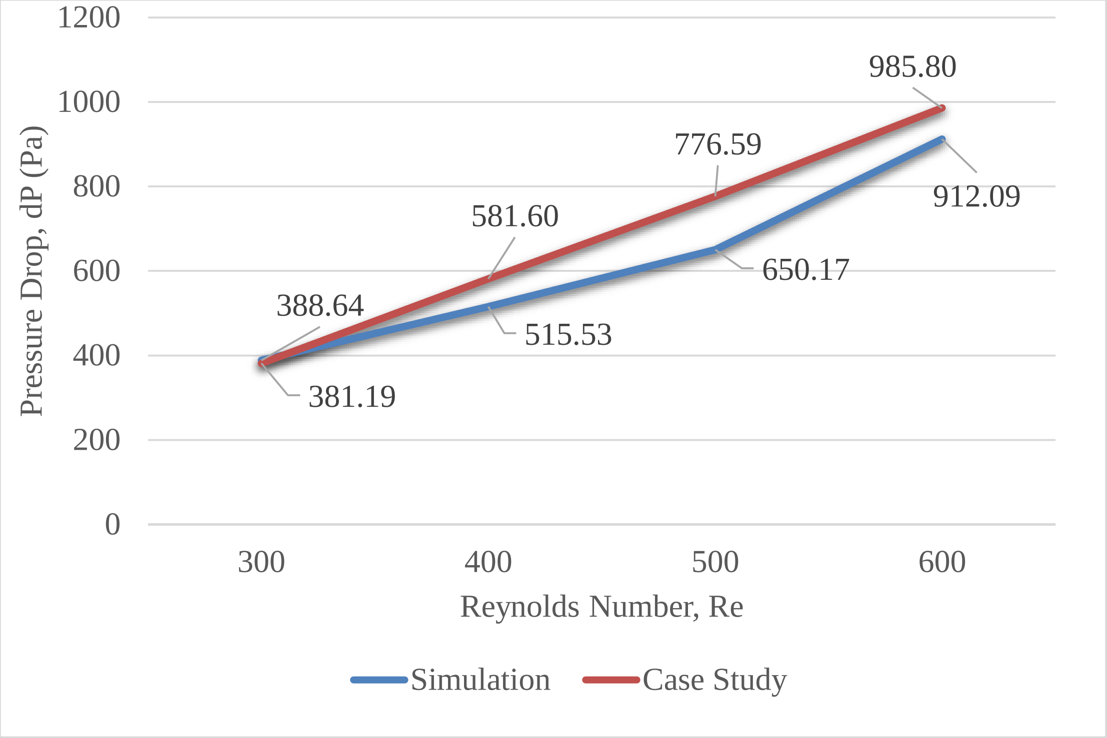


Figure 4.1: Validation of simulation

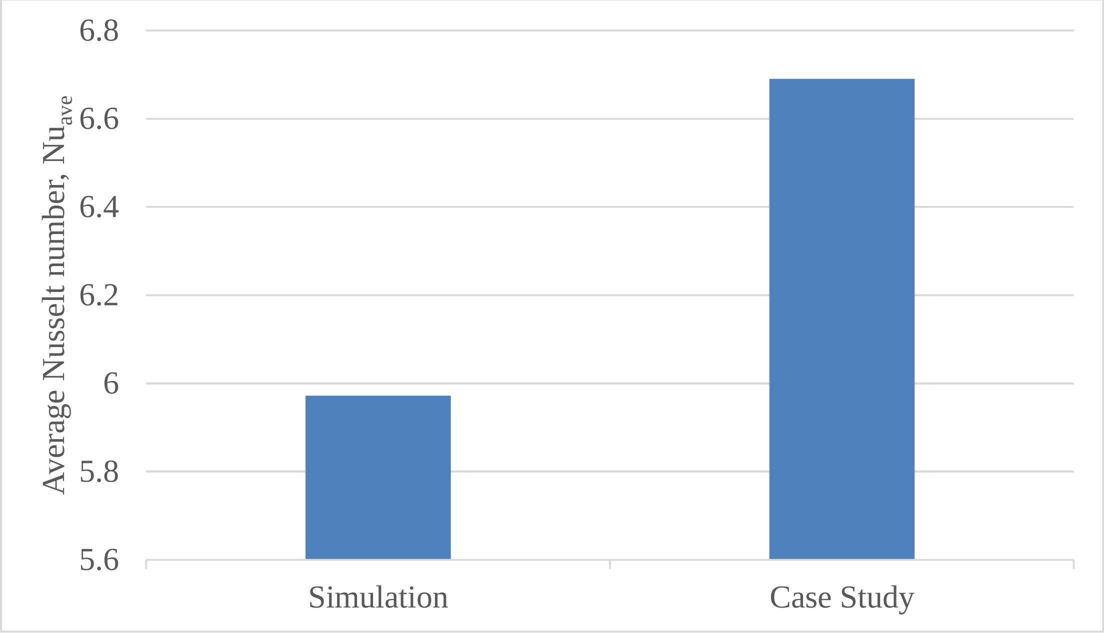


Figure 4.2: Comparison of average Nusselt number for plate fin

4.3 Pressure Drop

The effect of inlet velocity over the pressure drop is presented in two different plots which are shown in Figure 4.3 and 4.4 to clarify the results. The effect of velocity on the pressure drop by plate fin and oblique fin is the first to be compared. The pressured drop of the oblique fin is higher than the plate fin due to the presence of secondary flow passage. The secondary flow exists because of the oblique cut that provides entry exit for the flow and leads to the re-initialisation of the thermal boundary layer at the leading edge of each oblique fin thus reducing the boundary layer thickness [8]. Meanwhile, the plate fin has a lower pressure drop due to thickening of boundary layers. The momentum and heat effect of the wall is penetrating more deeply into the fluid as it moves along the wall as it moves without much influence on the pressure gradient.

A thinner boundary layer resulting in a higher magnitude of temperature gradient, and if the boundary layer is thicker, the magnitude of the temperature gradient at the wall is less. The results prove that oblique fin has a better performance to enhance heat transfer in MCHS compared to plate fin. This leads to the improvement on the oblique fin’s geometries.

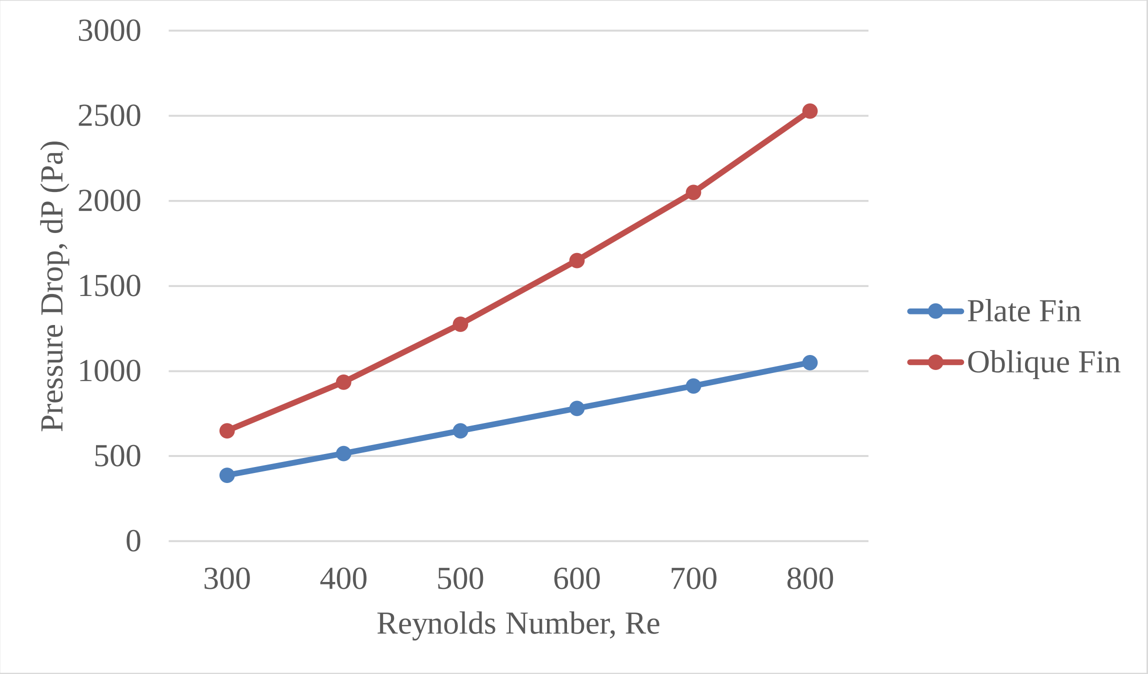


Figure 4.3: Comparison of pressure drop between plate fin and oblique fin

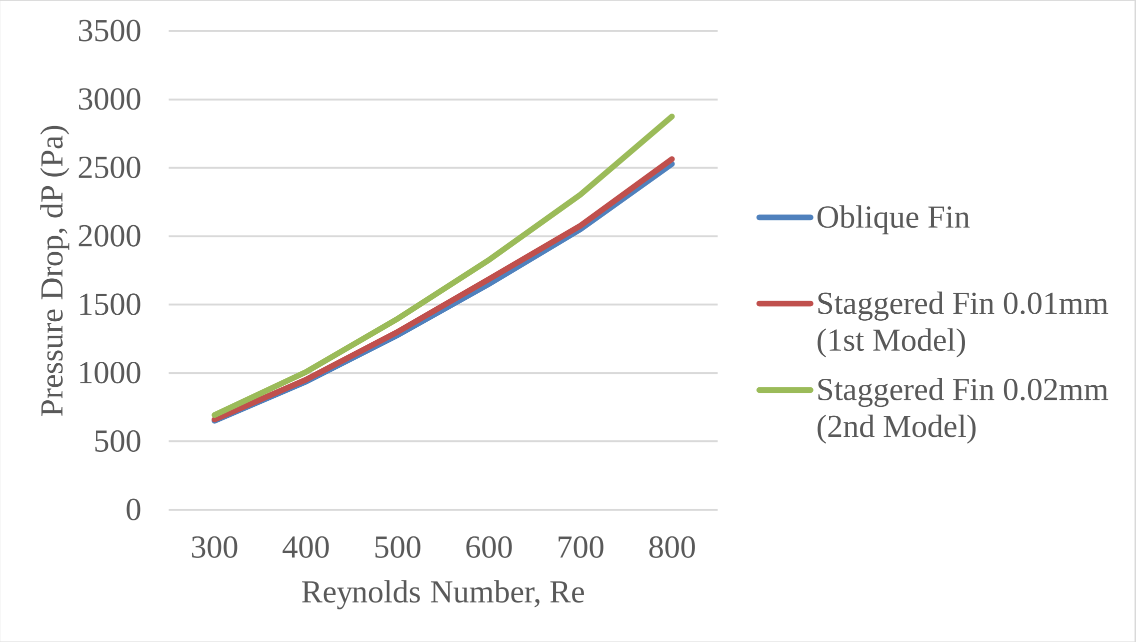


Figure 4.4: Comparison of pressure drop between oblique fin and staggered oblique fins

As Figure 4.4 shows, the pressure drop of the staggered oblique fins are much higher compared to the conventional oblique fin. This is because of the shock that the oblique fin encounters when the flow impinges resulting in early separation of the flows making it unable to use the wetted surface effectively. A smoother branching of secondary flow was generated in the staggered oblique fin thus increasing its performance. Meanwhile, the trend in Figure 4.3 shows that the second model of staggered fin shows a higher result in pressure drop compared to the first model due to the high thermal resistance presence. Increase in thermal resistance resulting the pressure drop to be increase [13].

4.4 Temperature Difference

Constant heat flux of 65 W/cm^2 and constant inlet velocity ranged 0.4 m/s to 1.07 m/s are applied for all the simulation done in this study. Due to the constant parameters, the heat transfer performance can be indicated by analysing the temperature difference on the outlet and the inlet of the fins. The temperature difference analysis is illustrated in Figure 4.5. The analysis is taken at Reynolds number 300 at 0.4 m/s velocity. The trend shows that the second model of staggered fin has the highest temperature difference compared to the first model of staggered fin and oblique fin respectively which is at 55.03K. Temperature difference is the driving potential for heat transfer adding in the enhancement of the design of fin. Therefore, it indicates that second model of staggered fin has the highest heat transfer performance.