# A COMPUTATIONAL STUDY ON THERMAL PERFORMANCE OF MICROCHANNEL HEAT SINKS

By

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and approved by

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**ABSTRACT OF THE THESIS**

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Thesis Director:

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In this research work, silicon microchannels are studied for computational analysis of heat transfer and fluid flow characteristics. Different designs of silicon microchannels were modeled and simulated in ANSYS FLUENT, evaluating thermal distributions for various boundary conditions. The operating parameters were inlet velocity, inlet temperature, and geometric configurations, under a constant surface heat flux condition. Microchannel cooling enhances heat transfer coefficients, thus allowing a high-power capacity. For a high heat-dissipating system, liquids provide better efficiency and capacity than air as a coolant. Hence water is used as the working medium in the microchannels.

Fabrication of silicon substrates prefers the rectangular geometry for microchannel design. For efficient design, geometric configurations considered in the modeling are varied from 100 x 50um to 500 x 200um. The length of microchannels fluctuates in between 1mm and 4.5mm.

The configurations considered were, Straight, U-shaped and Serpentine microchannels. Straight microchannels observed the best fluid flow characteristics. U-shaped microchannels had an increased pressure drop in the channels, but it showed

better heat transfer characteristics than straight microchannels. The most effective in terms of heat transfer characteristics were the Serpentine microchannels. Straight microchannel showed an optimized heat transfer and fluid flow characteristics. Hence variations in it were verified for improved cooling performance. Based on the analysis, there is enhanced heat transfer rates at the cost of a massive pressure drop.

## ACKNOWLEGMENTS

I am expressing my gratitude to my advisor Dr. Yogesh Jaluria for his technical advice, support and patience throughout my graduate studies at Rutgers. Without his valuable guidance and encouragement, I would not have been able to complete my master's Thesis. Dr. Jaluria has a profound impact on my path to seek a professional career, and I am deeply grateful for his invaluable advice, insightful vision, and great patience. I wish to express my gratitude to Dr. Jerry Shan, for his constructive suggestions and his time and efforts in reviewing the proposal and dissertation.

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## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

## NOMENCLATURE

| SYMBOL | DESCRIPTION | UNIT |
|---|---|---|
| ρ | Density | $kg/m^3$ |
| K | Thermal Conductivity | W/m K |
| Cp | Specific Heat | KJ/kg K |
| α | Thermal Expansion | $K^{-1}$ |
| U | Velocity | m/s |
| $D_h$ | Hydraulic Diameter | M |
| μ | Dynamic Viscosity | kg /m s |
| f | Friction Factor | - |
| P | Pressure | $N / m^2$ |
| Re | Reynolds Number | - |
| Pr | Prandtl Number | - |
| Q | Heat Transfer | W |
| $\dot{m}$ | Mass Flow Rate | kg / s |
| T | Temperature | K |
| Nu | Nusselt Number | - |
| q | Heat Flux | $W / m^2$ |
| h | Heat Transfer Coefficient | $W / m^2 K$ |
| W | Width | m |
| $W_c$ | Center-to-center distance of microchannel | m |
| H | Height | m |

# CHAPTER 1:

# INTRODUCTION

## 1.1 Motivation

With the fast development of microelectronics and other micro-components, the heat load and intensity of micro heat exchanger systems have drastically increased [1]. The performance reliability and life expectancy of micro-components are inversely affected by the rising temperature in the micro components. Cooling of these micro-components is achieved by microchannels which extract heat by forced convection. The microchannel uses a fluid coolant that should be located close to the heat source. Microchannels maximize the heat sink surface area and provide improved heat transfer coefficients, thereby allowing a higher power density of micro-components without increasing junction temperature or decreasing reliability [2].

Tuckermann and Pease [3] demonstrated that microchannels improve the cooling performance of electronic chips. Microchannels are either fabricated within the silicon chips or separately mounted on them. The heat transfer coefficient observed in microchannels is higher for laminar flow than that of turbulent flow. Heat transfer and fluid flow in the laminar regime for microchannels have been studied theoretically, experimentally and numerically. The results are compared for different approaches, examining transient state flow and heat boundary conditions [4]. The main purpose of the current study is to investigate computationally, the thermal performance of various configurations of microchannel heat sinks at different scales, thus finding an optimized solution for the microchannel heat sinks.

## 1.2 Literature review

A heat sink consisting of multiple microchannels with liquid flow is believed to be a promising cooling method for high heat dissipation micro-components. This is due to a relatively high heat capacity and heat removal efficiency offered by liquids rather than air [3]. The heat transfer performance and cooling characteristics of liquid flowing through rectangular microchannels were investigated experimentally. The results from microchannels being machined onto a plate provide significant data and considerable insight into the behavior of thermal characteristics. Thus, fluid velocity, liquid properties, and geometry of the microchannels all have a significant influence on the heat transfer characteristics and cooling performance of the microchannel [5].

For macro-scale rectangular channels, it is noticed that convective heat transfer is a critical factor. The ratio of the substrate thickness and the channel depth is not negligible in micro-scale systems. Therefore, combined conduction and convection, or conjugate heat transfer, need to be considered for numerical analysis [6]. The conjugate heat transfer model was implemented in COMSOL and the numerical results were validated by comparisons with analytical results. The simulations were performed for silicon, aluminum, and copper with different mass flow rates. Results were obtained for temperature rise and pressure drop. The study shows that the maximum temperature rise for the coolant is in silicon microchannels [7].

The fabrication process of the silicon based microchannels is usually difficult for circular cross-sections, leading to the use of noncircular and mostly rectangular cross-sections. Most experiments to date have explored ways to improve the thermal performance of the straight rectangular microchannel heat sinks. This is done by optimizing the aspect ratio of the straight rectangular microchannels, for increasing the convective heat transfer by the coolant.

Microchannels with bends are encountered in several engineering systems, particularly in chemical processing and heat exchangers. The U-shaped and serpentine microchannels were studied for the flow behavior, but the heat transfer characteristics were not included. For serpentine and U-shaped micro-channels, the additional pressure drop increases sharply with Reynolds number and decreasing hydraulic diameters [8].

Considering U-shaped microchannels, three numerical models, namely one channel, two-channel, and three-channel models, have been simulated computationally. By comparing the numerical predictions with experimental data, the two-channel model is shown to be accurate enough to predict the flow and heat transfer performance of the entire microchannel heat sinks [9].

The design optimization of microchannels is another important aspect in the study of micro-cooling systems. Even though there are substantial studies on the design optimization of the thermal system, most of the optimization studies for microchannel cooling were based on experimental results. Therefore, results are limited by the number of samples and experimental data range.

An experimental and numerical combined approach was applied to study the thermal and fluid performance of microchannel heat sinks. Silicon microchannel heat sinks were designed and fabricated, and the data measurement instruments were calibrated with a temperature measurement uncertainty within ±0.5. Multi-microchannel heat sinks of different geometries (Straight, U-shaped and Serpentine channels) were studied with varying flow rates and heat fluxes. The components that contribute to the thermal resistance were identified and pressure drop were studied including the inlet-outlet loses, developing flow losses, and frictional flow losses [10].

A good agreement between the experimental data and numerical results showed that single-channel models can simulate thermal behavior of the entire heat sink by applying appropriate assumptions and boundary conditions. The experimental results can then be used to improve the numerical models and vice versa [11]. In the current study, different configurations such as; straight channels, U-shaped channels, and serpentine channels were tested through computational analysis in ANSYS Fluent. The objective of this study is to investigate the heat transfer characteristics of multi-microchannel heat sinks. The simulation results from the analysis where validated.

# CHAPTER 2:

# MODEL, SETUP AND VALIDATION

## 2.1 Material Selection

There are different types of materials that can be used for the microchannel heat sink fabrication like copper, iron, aluminum, steel, stainless steel, and silicon. Usually silicon substrate is fabricated for microchannel heat sinks because of its outstanding electronic and mechanical properties. Hence, most of the microfabrication technologies use single-crystal silicon for its high precision, high strength and high reliability in developing microchannels. The table below represents a list of silicon's thermal properties.

| Density ($kg/m^3$) | Thermal Conductivity (W/m K) | Specific Heat (KJ/kg K) | Thermal Expansion ($10^{-6}$ / $^oC$) |
|---|---|---|---|
| 2328 | 157 | 0.714 | 2.33 |

Table 2.1. Silicon Thermal Properties

## 2.2 Computational Model

Initially, straight, U-shaped and serpentine shaped configurations of a microchannel heat sinks were designed. Each of these configurations was computationally analyzed for variation in size of a rectangular microchannel. Their results will be discussed in the next chapter. The following figure shows these three major types of microchannel heat sinks.

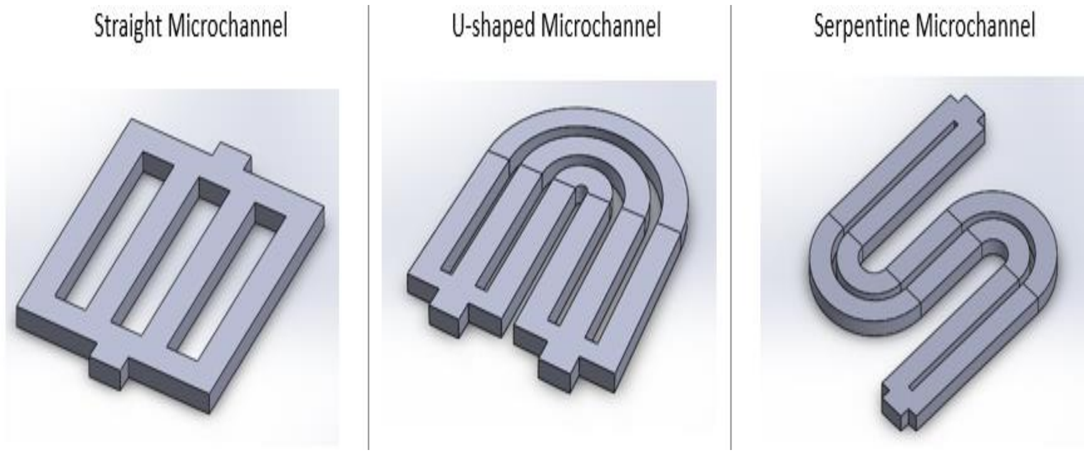



Figure 2.1 Schematic of different microchannel heat sink configurations considered

This research not only investigates these three configurations but also covers the various modifications in straight channels. The modifications were then analyzed and compared with regular straight channels. The figure below shows the modifications which are straight channels with fins, varying width and reduction in width.

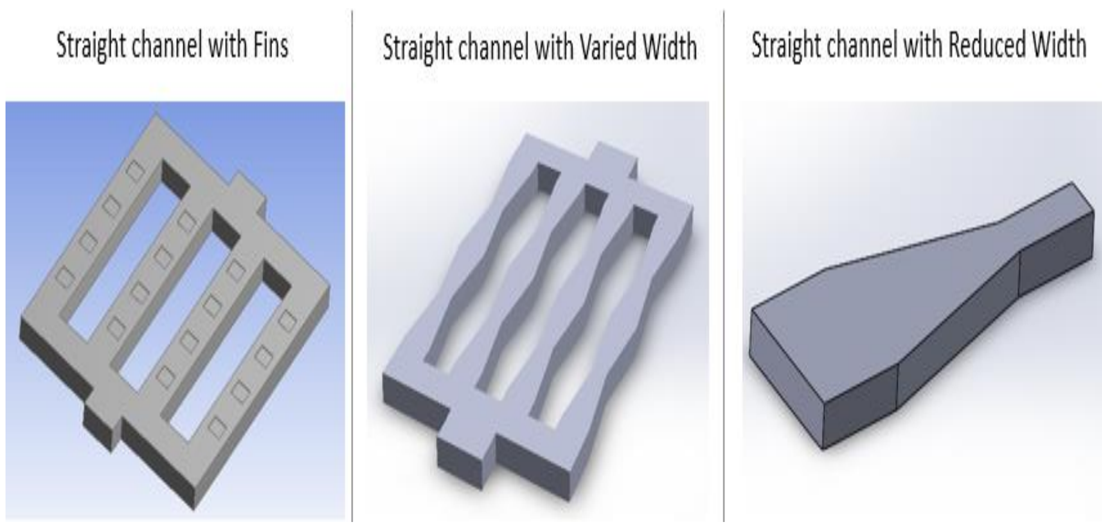



Figure 2.2 Schematic of different modifications in straight microchannels

**2.2.1 Heat Transport Mechanism**

As discussed in the previous chapter, it is usually difficult to fabricate circular cross-sectional microchannels, which leads to the usage of non-circular and mostly rectangular cross-sections for the silicon base.

For macro-scale rectangular channels, it is noticed that convective heat transfer is a critical factor. But in micro-scale systems, conjugate heat transfer needs to be considered for numerical analysis. Also, the effect of radiation heat transfer is minimal compared to overall heat dissipation due to which it can be neglected for this study.

Metais and Eckert [12] identified that, for laminar flow in horizontal tubes the effect on the heat transfer is either free, forced or mixed convection. Considering the velocities used in this study, free convection can have significant amount of effect on the heat transfer.

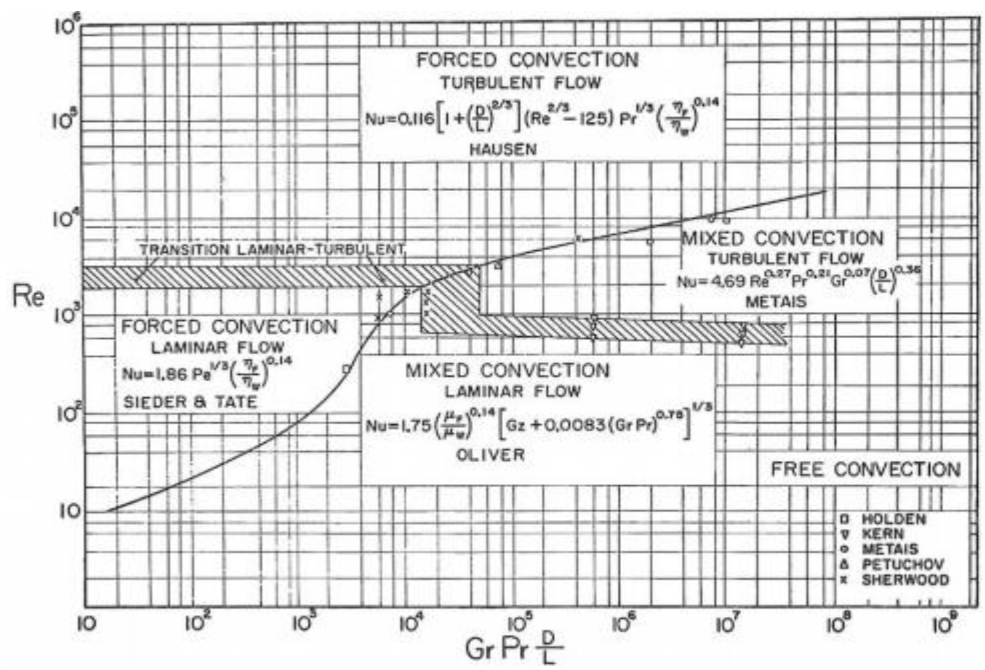



Fig 2.3 Free, forced and mixed convection regimes for flow in horizontal tubes

(Taken from Metais and Eckert)

### 2.2.2 Hydraulic and Heat Transfer Parameters

Dimensionless parameters can be used to describe fluid and heat transfer characteristics which allow us to compare results from different results in the of literature.

**1**. **Reynolds Number**

$$Re = \frac{\rho U D_h}{\mu}$$

Reynolds number is used to predict flow patterns.

**2**. **Skin Friction Coefficient**

$$f = \frac{\frac{\Delta P}{L} D_h}{\frac{1}{2}\rho U^2};$$

This is simplified Darcy's friction factor or fanning friction factor equation.

**3. Nusselt number**

It is defined as the ratio of convective conductance to the pure molecular thermal conductance. Nusselt number for axial wall heat flux in laminar flow regime as per Peng and Peterson [5],

$$Nu = 0.1165 * \left(\frac{D_h}{Wc}\right)^{0.81} * \left(\frac{H}{W}\right)^{-0.79} * Re^{0.62} * Pr^{1/3}$$

**4. Heat Transfer Rate**

It is the most relevant parameter that describes the heat transfer rate (Q). The heat transfer rate is calculated from the equation

$$Q = \dot{m} \times Cp \times \Delta T$$

**2.2.3 Physical Model**

The computational model is formulated for six types of microchannels mainly follows straight, U-shaped and serpentine and three modifications in straight microchannels. Each of these microchannels is investigated for different aspect ratios and various fluid flow velocities through the rectangular duct. The rectangular duct's cross-sectional area varies from 100 x 50 $\mu m^2$ to 500 x 200 $\mu m^2$. Water is used as the coolant and it has velocities starting from 0.5 m/s to 5 m/s.

SolidWorks is used to design the microchannels and is then imported in Ansys Fluent Workbench to solve each of the cases for the following boundary conditions. The boundary conditions are, a constant heat flux of 1000000 W/ $m^2$ is imposed at the bottom of the silicon substrate. The sidewalls of the substrate are taken as adiabatic and the top wall has free convection. The heat transfer coefficient of air for free convection with ambient temperature of 300 °K has a value in between 10-100. The heat transfer coefficient of air is calculated for horizontal plate as 75 W/$m^2$-K for the ambient temperature of 300 °K.

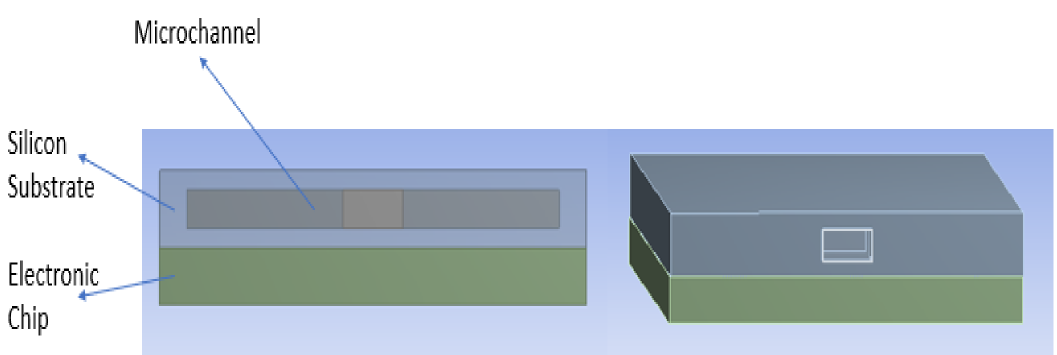



Figure 2.4 Physical Model

## 2.3 Model Validation and Grid Verification for Straight Microchannel.

Optimization of the straight rectangular microchannel has been the priority of most of the studies on microchannels over decades. Tuckerman and Pease [3] were pioneers who demonstrated that the electronic chips can be cooled effectively with the help of silicon microchannels. This led to studying the enhancement of the thermal performance of silicon microchannels. The enhancement in cooling performance of the straight microchannel is mostly correlated with the channel spacing, surface roughness and viscosity of the fluid.

Peng and Wang [14] investigated rectangular microchannels for channel spacing with hydraulic diameters ranging between 133 µm and 367 µm for velocities 0.5-1.5 m/s. Their study showed that the cross-sectional aspect ratio had a significant effect on the friction factor. Thus, increasing the width or decreasing the height of the microchannel enhances the heat transfer. They also concluded that the laminar heat transfer will be augmented by enlarging the hydraulic diameter or decreasing the center-to-center distance of the microchannels.

Xu [16] considered liquid flow for hydraulic diameters 30 to 344 µm at Reynolds number of 20 to 4000 in his research. Unlike Peng and Wang, the results obtained by Xu followed the fluid flow behavior as per the Navier-Stokes equation. Liu and Garimella [15] supported this argument and proved that characteristics of flow in microchannels offer reliable predictions for rectangular microchannels over a hydraulic diameter range of 244 to 974 µm.

Jung and Kwak [16] tested straight rectangular microchannels for widths of 100, 150 and 200 µm with a height of 100 µm and a length of 15 mm. The measured Reynolds number and friction factor constants are compared with theoretical values for conventional fluid flow behavior and are satisfactory. Thus, the work of Jung and Kwak helped in considering the geometric properties and velocities for the present computational study of microchannels. Numerical Analysis is conducted on straight rectangular microchannels for the geometric properties shown in Table 3.37.

| Width (W) | Height (H) | Hydraulic Diameter (Dh) | Aspect Ratio (α) |
|---|---|---|---|
| 100 | 50 | 66.6667 | 0.5 |
| 100 | 100 | 100 | 1 |
| 150 | 100 | 120 | 0.66667 |
| 200 | 100 | 133.333 | 0.5 |
| 250 | 100 | 142.857 | 0.4 |
| 500 | 200 | 285.714 | 0.4 |

Table 2.2 Geometric Parameters for straight microchannel

The obtained value of Reynolds number in different cross-sections with respective hydraulic diameters are shown below.

| Reynolds Number (Re) | | | | | | |
|---|---|---|---|---|---|---|
| Velocity (m/s) | 0.5 | 1 | 2 | 3 | 4 | 5 |
| Cross-section | | | | | | |
| 100 x 50 | 37.4 | 74.9 | 149.8 | 224.7 | 299.6 | 374.5 |
| 100 x 100 | 56.1 | 112.3 | 224.7 | 337.1 | 449.4 | 561.8 |
| 150 x 100 | 67.4 | 134.8 | 269.6 | 404.5 | 539.3 | 674.2 |
| 200 x 100 | 74.9 | 149.8 | 299.6 | 449.4 | 599.2 | 748.9 |
| 250 x 100 | 80.2 | 160.5 | 321.0 | 481.5 | 642.0 | 802.6 |
| 500 x 200 | 160.5 | 321.0 | 642.1 | 963.1 | 1284.1 | 1605.1 |

Table 2.3 Reynolds Number for straight microchannels

# CHAPTER 3:

# COMPUTATIONAL STUDY

## 3.1 Computational Study for Straight Microchannel

Straight Microchannels are the basic design of water-cooled silicon heat sinks and are considered for comparison with other heat sinks. Here six types of cross-sections of the microchannel are examined for the variations in thermal and fluid properties for velocities 0.5 - 5m/s. The pressure-drop in the microchannel, temperature at different locations and heat flux at the top wall of the substrate are some of these thermal and fluid variations. The following figure show the computational model for straight microchannels.

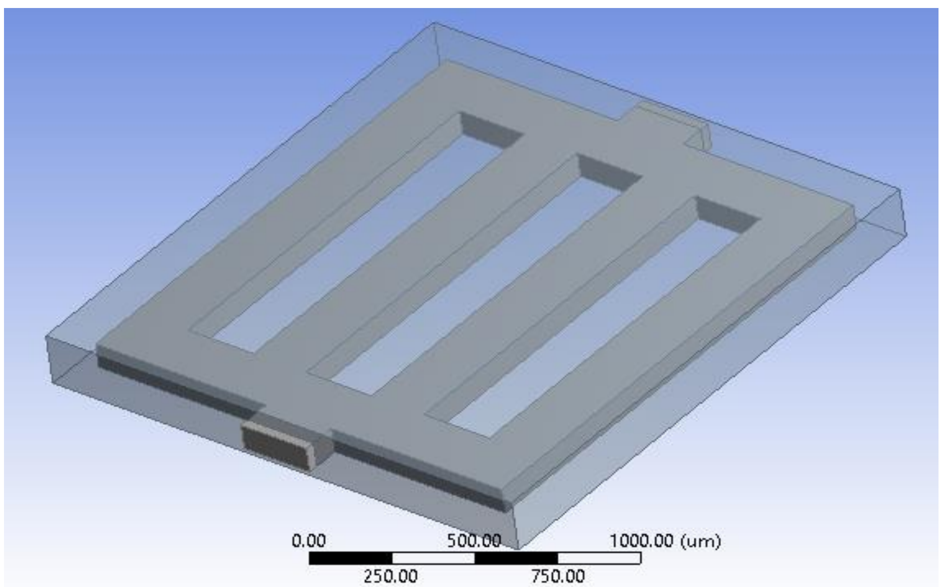



Figure 3.1 Computational model of straight microchannel.

### 3.2 Computational Study for U-shaped Microchannel

A microchannel heat sink with a 180° bend is examined for pressure-drop in the microchannel, temperature at different locations, and heat flux at the top wall of the substrate. Three U-channels are fabricated in the heat sink, separated with a 100μm distance. When the fluid approaches this U-shaped curvature, there is a vortex formulated at the corner which causes temperature rise at the corner. Then, the temperature increases till the fluid leaves the channel. This concludes that the heat transfer performance in the curvature is better than at other places of U-shaped microchannel. It is observed that the temperature of water, near to the outlet of the microchannel may be almost same as the substrate despite the fluid flow through it. This should be avoided for a better heat transfer condition by considering the geometrical design.

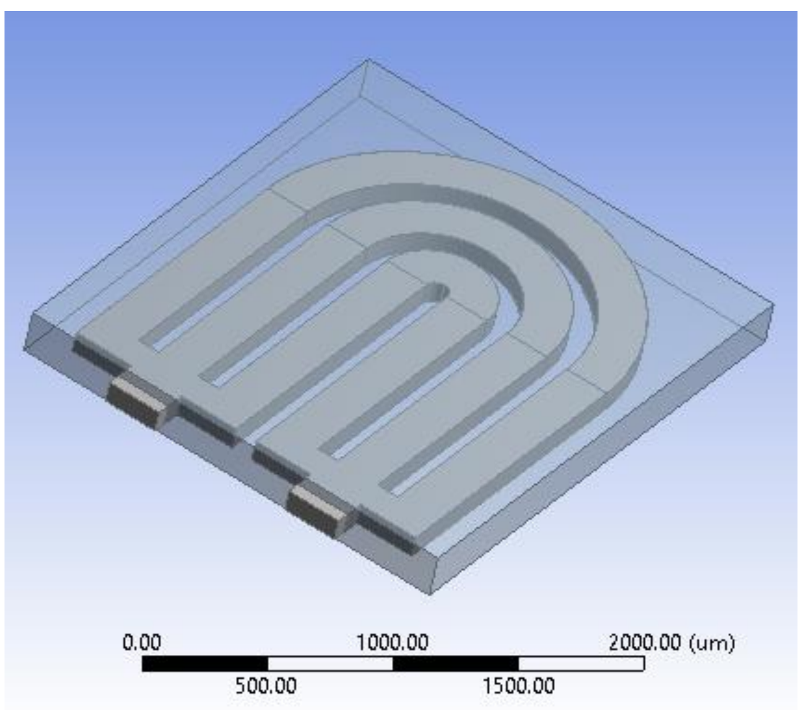



Figure 3.2 Computational Model of U-shaped Microchannel.

### 3.3 Computational Study for Serpentine Microchannel

Here two numbers of serpentine microchannels are fabricated in the silicon substrate separated with 100µm and have a total of two bends in the microchannel. Because, with the increasing number of bends, the pressure in the microchannel increases. Also, many bends reduce the local flow circulation, resulting in a very low output velocity. The previously obtained results for the serpentine microchannel show that a more efficient temperature distribution can be achieved with a higher pressure-drop to be compensated. However, the pressure drop in the regular case is still much higher as compared to the straight microchannels. Pressure-drop in the microchannel, the temperature at different locations, and heat flux at the top wall of the substrate are formulated below for the same velocity variations.

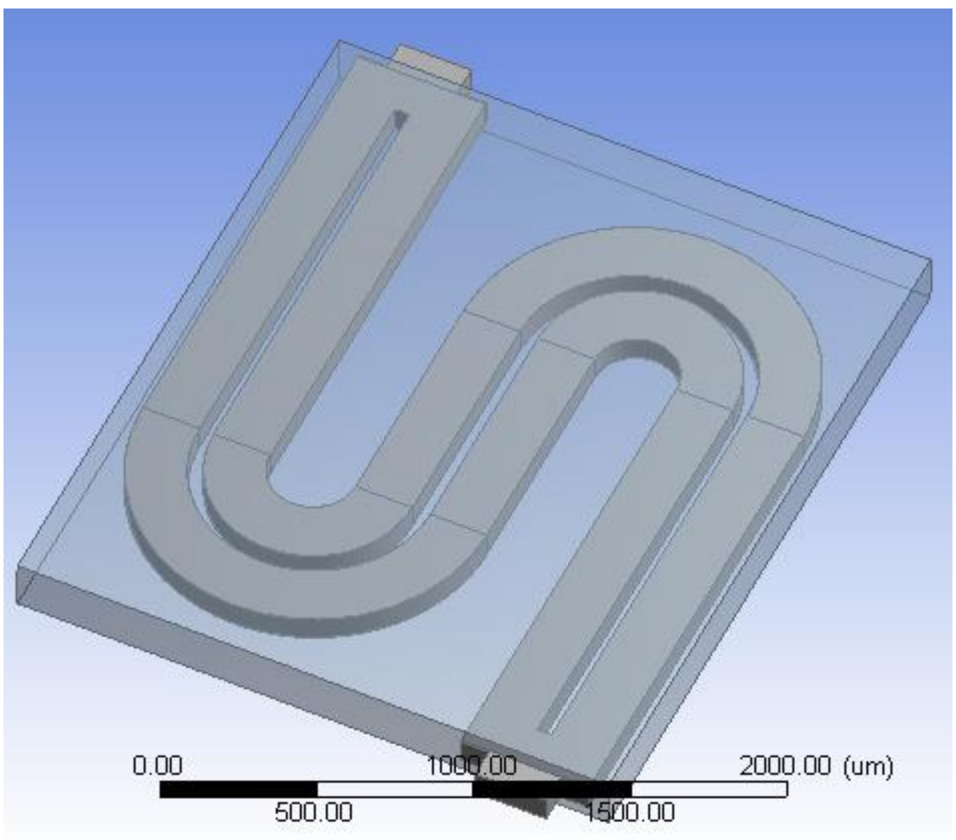



Figure 3.3 Computational Model of Serpentine Microchannel.

### 3.4 Effectiveness of modifications in Straight Channels

Microsystems is a fast-emerging field with increasing demands on heat flux inputs. Hence it is necessary to provide enhanced heat transfer rates for better working conditions and reliability of the system. As an attempt to solve this issue, modifications in the channel design and different coolants are required for improved thermal performance. In this study different channel designs in straight rectangular microchannels are investigated, these are straight channels with fins, varying width, and reduction in width.

#### 3.4.1 Computational Study for Straight Microchannel with fins

A comparison between circular and square fin was conducted by Zhao [13]. Square / rectangular cross-section of the fin is used over circular cross-section because a lower pressure difference and temperatures at the output are achieved. The present study thus computationally simulates straight rectangular microchannels with 4 pin fins in a single microchannel. The pin fin tip introduced in straight microchannels, allows increased heat transfer area, and enhances the flow rates by reducing wake formation. As a result, heat transfer is enhanced, and cooling capacity of the heat sink is increased.

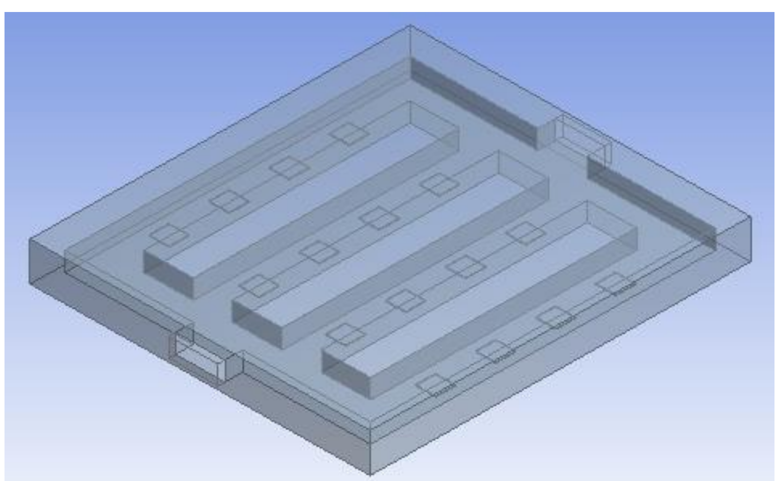


Figure 3.4 Computational Model of Straight Microchannel with Fins.

### 3.4.2 Computational Study for Straight Microchannel with Varying Width

In varying width type of straight microchannel, the width of the rectangular microchannel is reduced to half its length and then again restored to its original length. This modulation of width is done two times before the fluid reaches the output. Such variations affect the temperature at the top wall of the silicon substrate, pressure in the microchannel and velocity of the fluid through the microchannel.

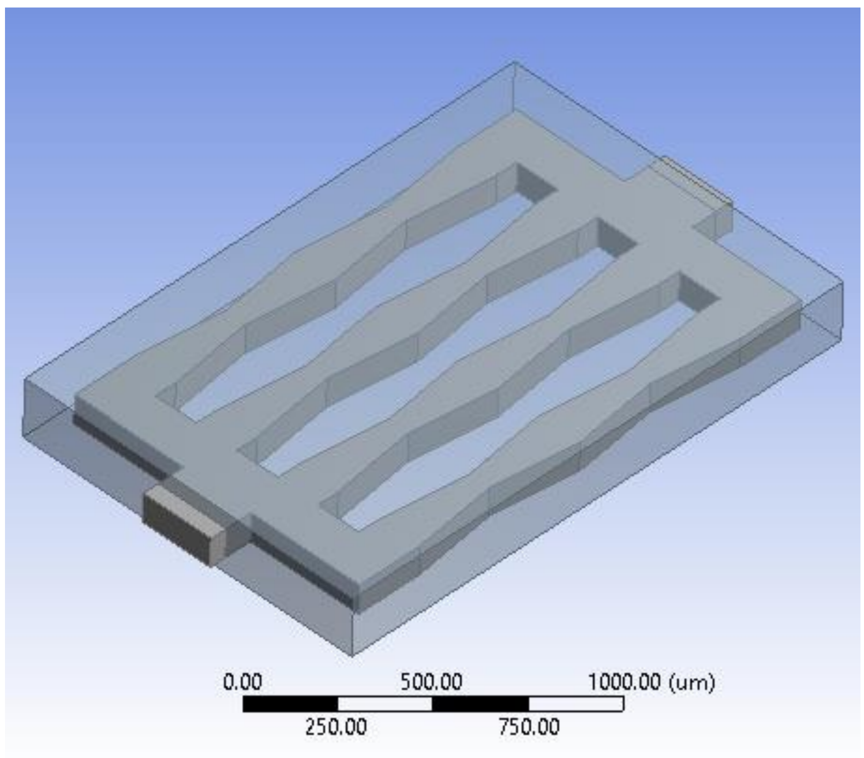



Figure 3.5 Computational model of straight microchannel with varying width

### 3.4.3 Computational Study for Straight Microchannel with Reduced Width

For optimization of straight microchannel the reduced width design is implemented in this study. The input of the microchannel has a larger width as compared to straight microchannels and the width gradually decreases over the length to obtain a smaller cross-sectional output. Since the input has a large cross-section it is better to use two microchannels to cover maximum area of the silicon substrate. Pressure-drop in the microchannel, the temperature at different locations, and heat flux at the top wall of the substrate are formulated below for the same velocity variations.

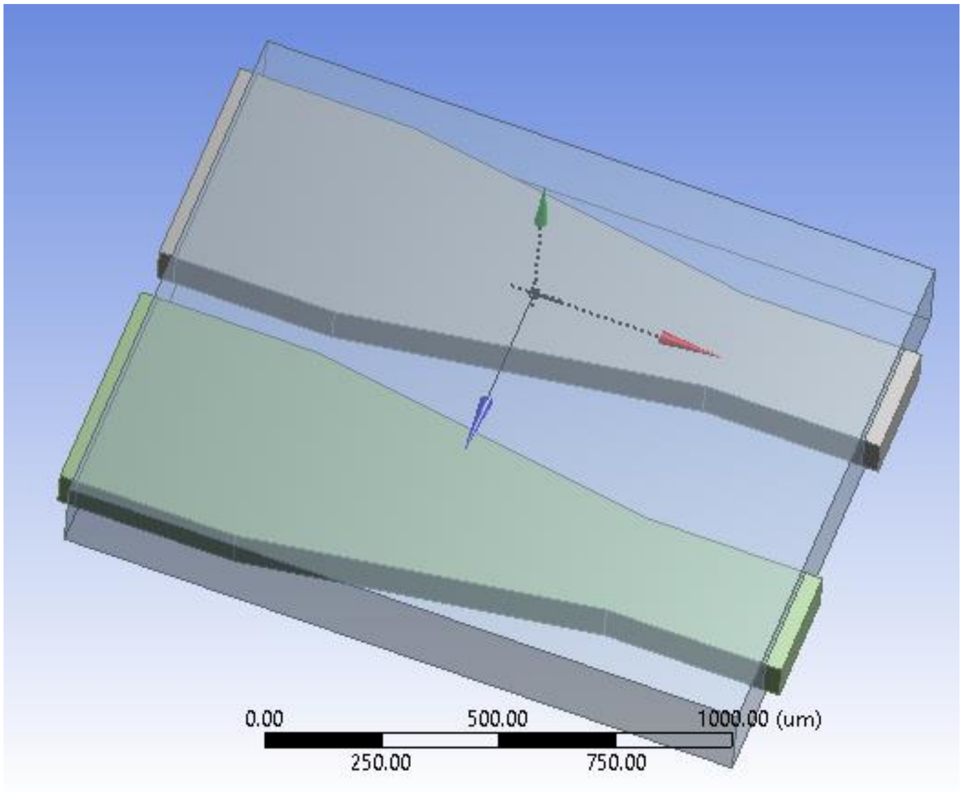
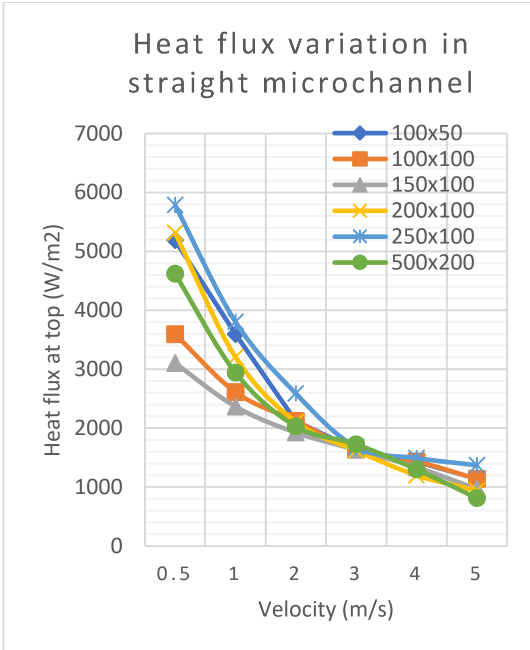
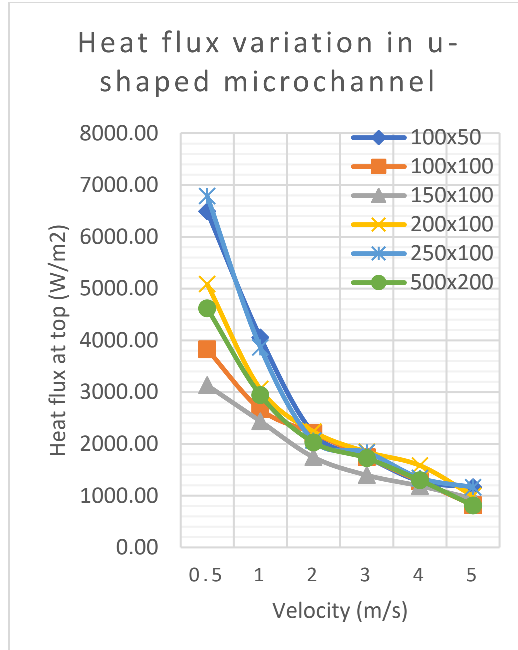
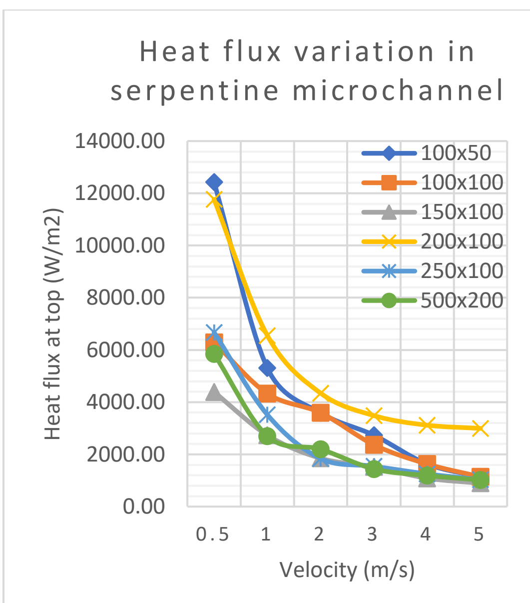
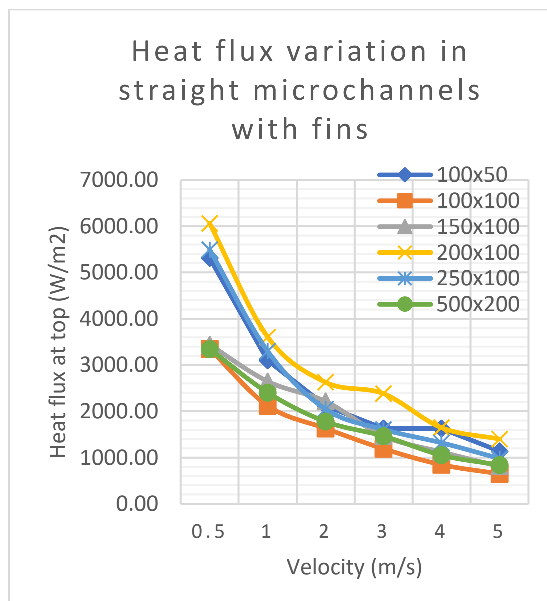



Figure 3.6 Computational Model of Straight Microchannel with Reduced Width


Heat flux variation in straight microchannel
7000
6000
5000
4000
3000
2000
1000
0
Heat flux at top (W/m2)
100x50
100x100
150x100
200x100
250x100
500x200
0.5
1
2
3
4
5
Velocity (m/s)


Heat flux variation in u-shaped microchannel
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
Heat flux at top (W/m2)
100x50
100x100
150x100
200x100
250x100
500x200
0.5
1
2
3
4
5
Velocity (m/s)


Heat flux variation in serpentine microchannel
14000.00
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
Heat flux at top (W/m2)
100x50
100x100
150x100
200x100
250x100
500x200
0.5
1
2
3
4
5
Velocity (m/s)


Heat flux variation in straight microchannels with fins
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
Heat flux at top (W/m2)
100x50
100x100
150x100
200x100
250x100
500x200
0.5
1
2
3
4
5
Velocity (m/s)

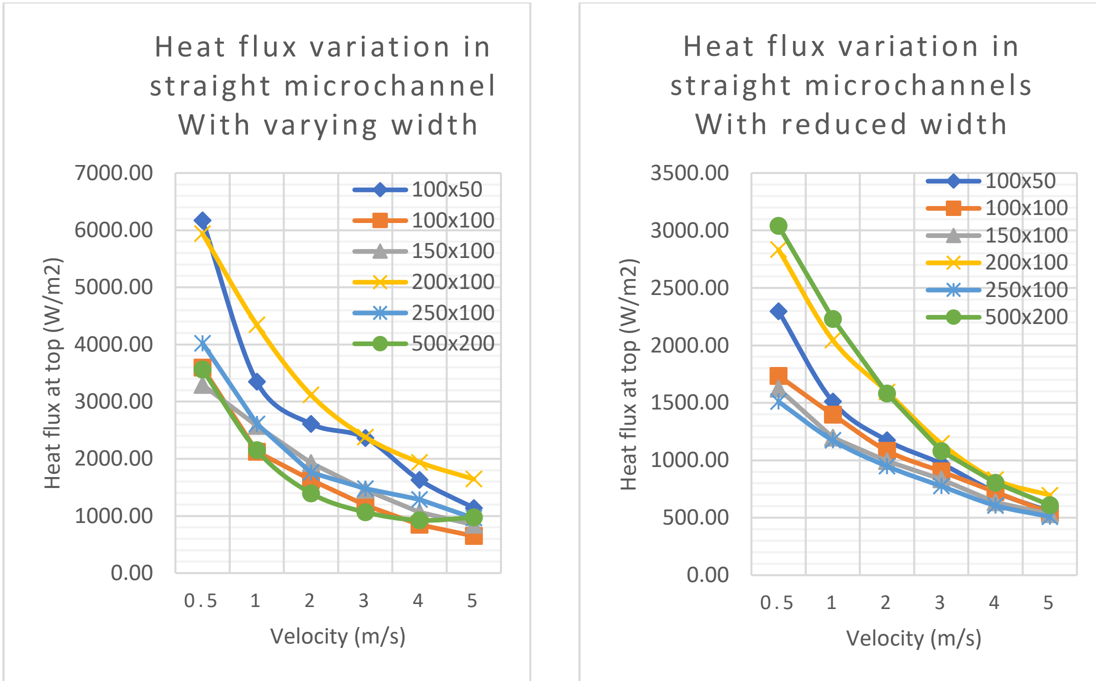
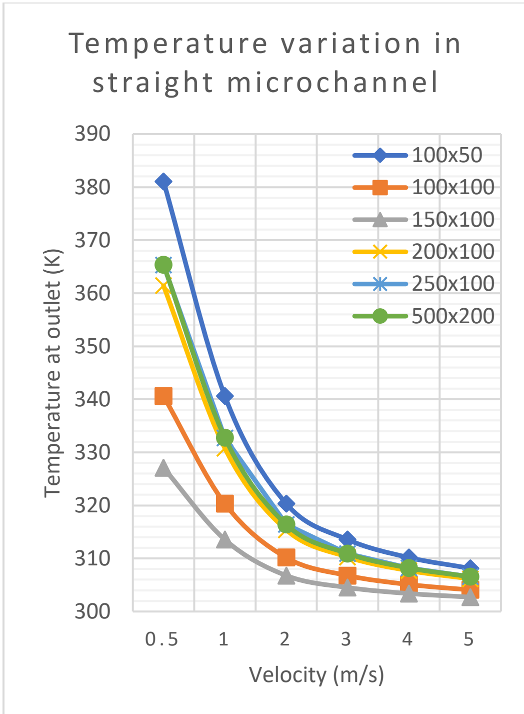
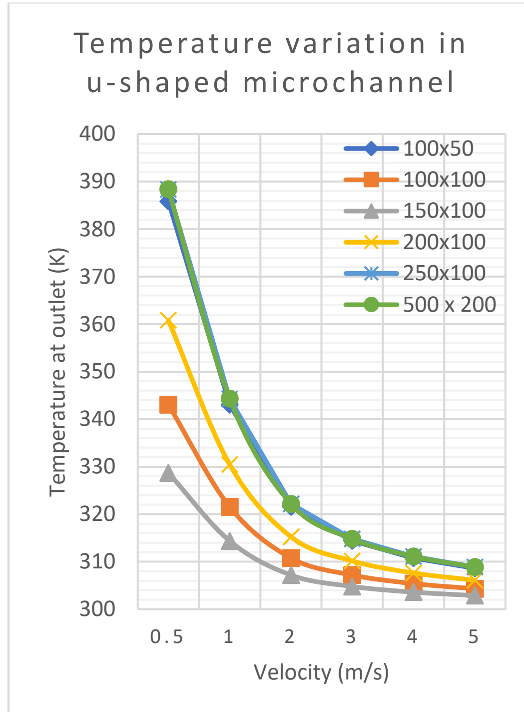



Figure 3.7 Heat flux vs velocity variation in all microchannels

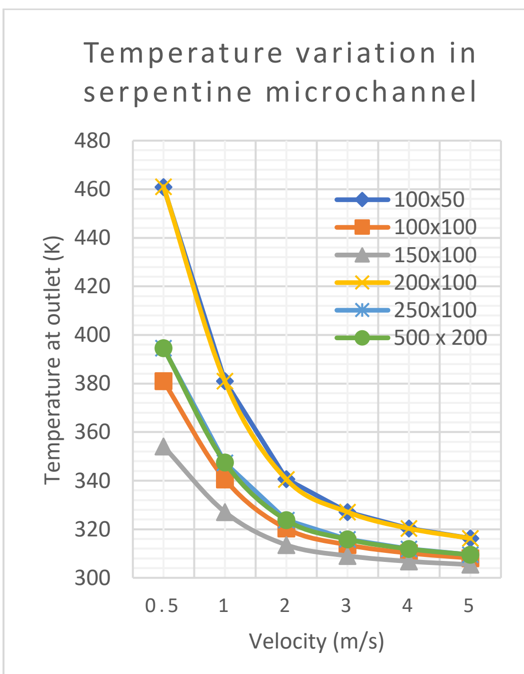
Lower the heat flux at top of the silicon substrate better the cooling performance of the microchannel. Comparing a single cross-section, we find that straight microchannel has the highest heat flux at the top, and the lowest is for straight microchannels with reduced width. Heat flux obtained at the top of the silicon substrate linearly decreases as the inlet velocity of the fluid through microchannel is increased, as expected. Comparing the heat flux for 100 x 50 μ$m^2$, 100 x 100 μ$m^2$, and 150 x 100 μ$m^2$, it is observed that heat flux is reduced as a result of the increase in the cross-sectional area of the microchannel.



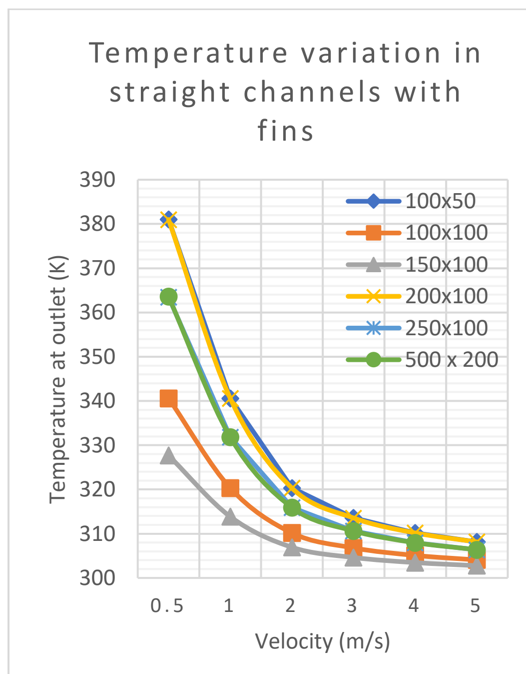
Temperature variation in straight microchannel
Temperature at outlet (K)
390
380
370
360
350
340
330
320
310
300
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500x200

Temperature variation in u-shaped microchannel
Temperature at outlet (K)
400
390
380
370
360
350
340
330
320
310
300
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500 x 200

Temperature variation in serpentine microchannel
Temperature at outlet (K)
480
460
440
420
400
380
360
340
320
300
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500 x 200

Temperature variation in straight channels with fins
Temperature at outlet (K)
390
380
370
360
350
340
330
320
310
300
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500 x 200

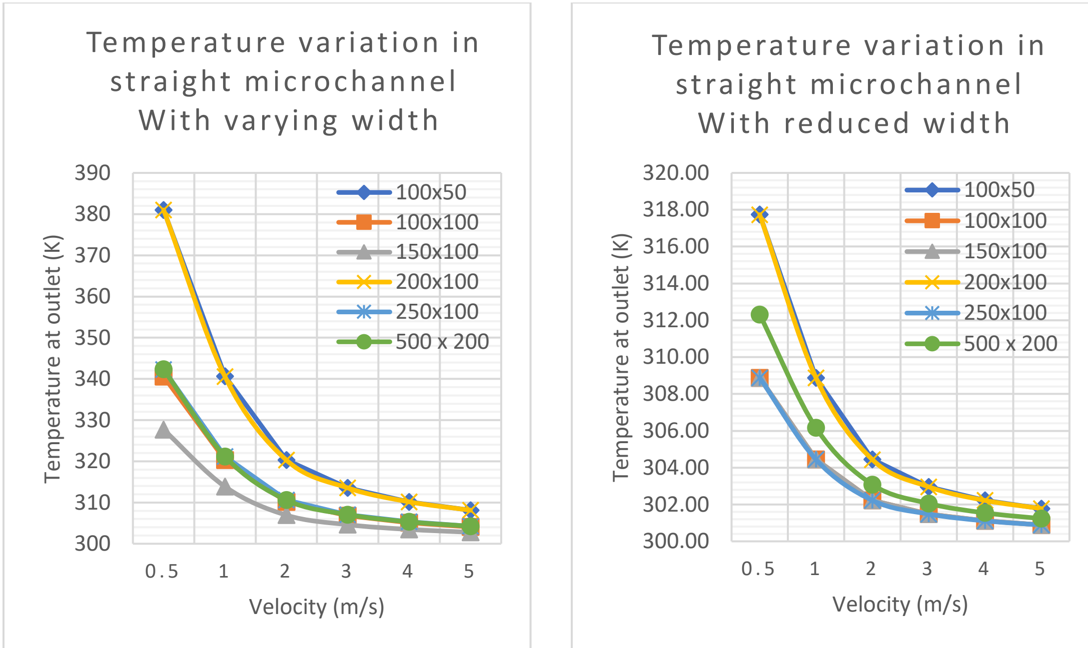
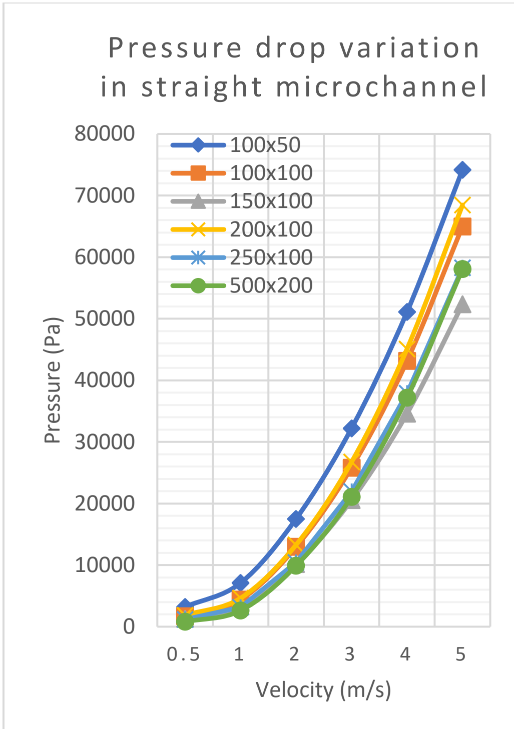
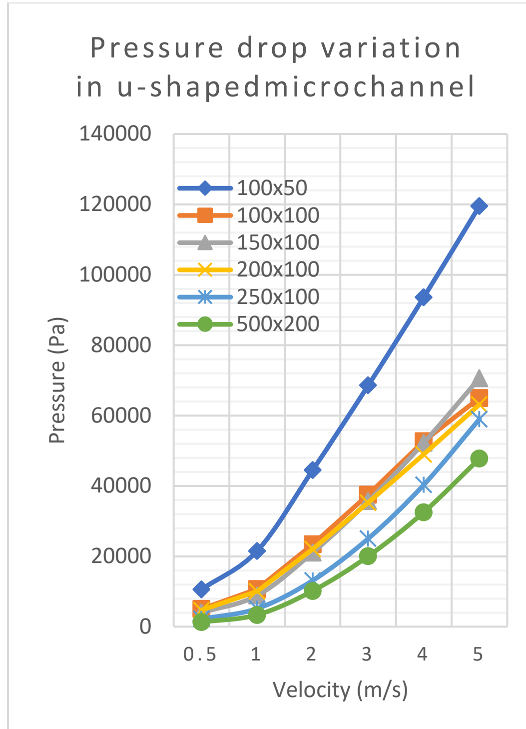
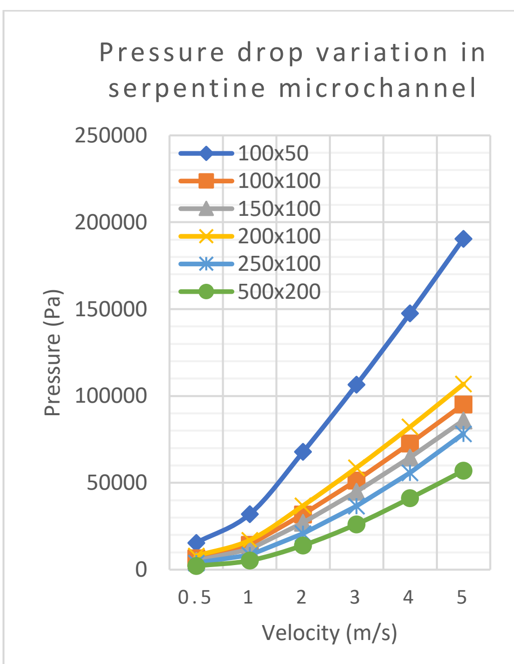


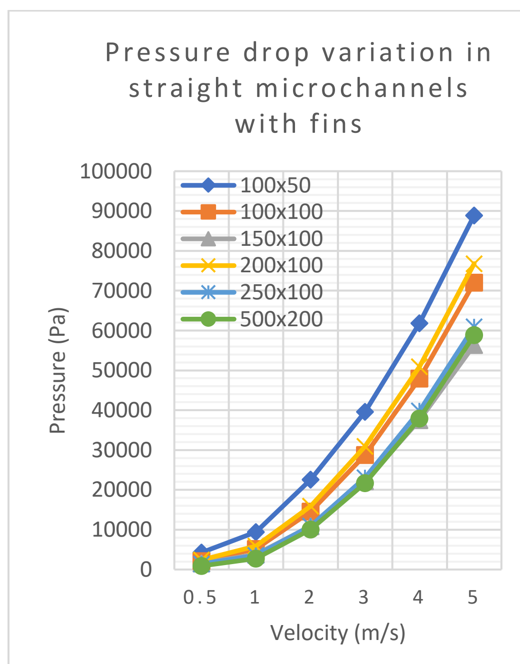

Figure 3.9 Temperature at outlet vs velocity variation in all microchannels

The fluid does not have enough time to sit and absorb the heat from the substrate as the velocity through the microchannel increases. Thus, the outlet temperature of fluid decreases with an increase in fluid velocity. For a specific velocity, the more the temperature observed at the outlet better will be the cooling performance. In this case, the serpentine microchannel provides the best thermal performance. Now comparing the temperatures for 100 x 50 µm2, 100 x 100 µm2, and 150 x 100 µm2, it is observed that the temperature at the outlet is decreased when the inlet area increases.


Pressure drop variation
in straight microchannel
Pressure (Pa)
80000
70000
60000
50000
40000
30000
20000
10000
0
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500x200


Pressure drop variation
in u-shapedmicrochannel
Pressure (Pa)
140000
120000
100000
80000
60000
40000
20000
0
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500x200


Pressure drop variation in
serpentine microchannel
Pressure (Pa)
250000
200000
150000
100000
50000
0
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500x200


Pressure drop variation in
straight microchannels
with fins
Pressure (Pa)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0.5
1
2
3
4
5
Velocity (m/s)
100x50
100x100
150x100
200x100
250x100
500x200

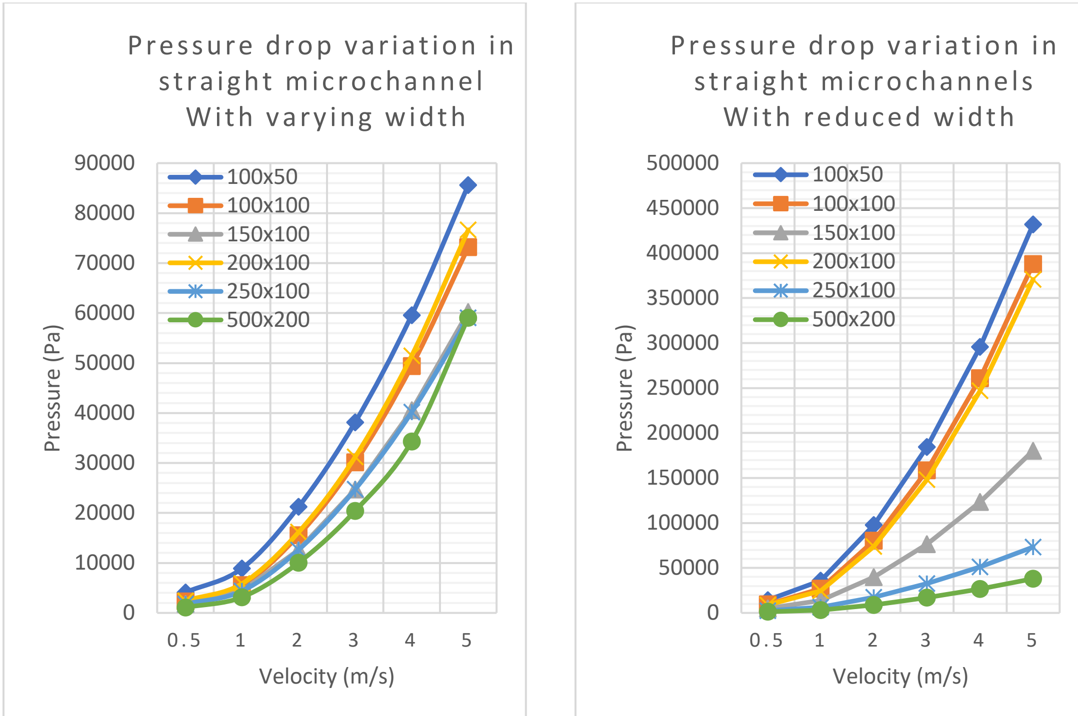



Figure 3.8 Pressure drop vs velocity variation in all microchannels

The pressure-drop in the microchannel drastically increases with an increase in the inlet velocity of the fluid. If the fluid has a larger pressure drop, then a high pumping power is required to redirect the fluid through the microchannel. Hence a lower pressure-drop in the microchannel is preferred to achieve higher fluid performance. Comparing the pressure drop for 100 x 50 um2, 100 x 100 um2, and 150 x 100 um2, it is observed that pressure drop is reduced, as a result of the increased flow rate through the microchannel.

## CHAPTER 4:

## COMPUTATIONAL RESULTS

### 4.1 Thermal Performance

As explained in the previous chapter, the computational module for 100 x100 and 150 x 100 was initially validated. After which four more cases for different sizes of microchannel cross-sections and silicon substrates were analyzed. In some cases, two separate microchannels are implemented in the silicon substrate to get better accuracy. Figures below show the temperature variation and heat flux obtained at the top of the silicon substrate for all types of microchannel cases at a velocity of 2 m/s.

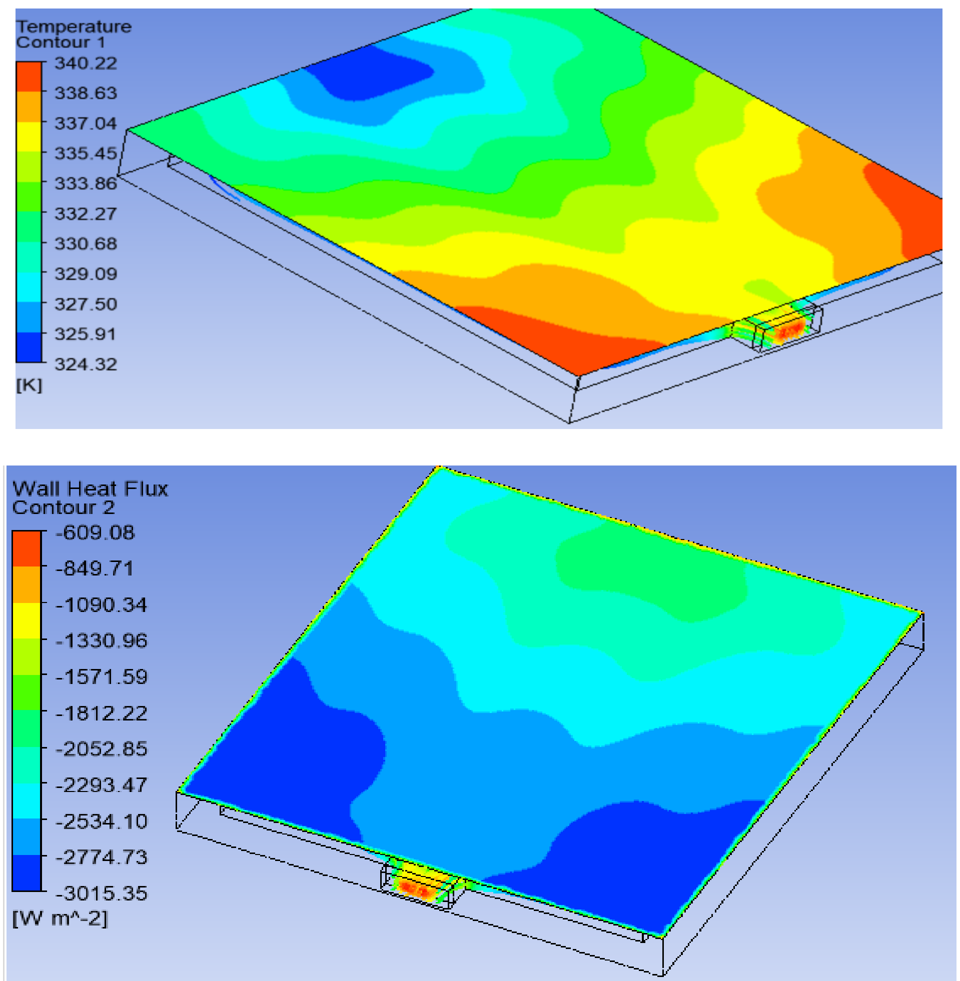



Figure 4.1 Thermal performance of straight microchannel

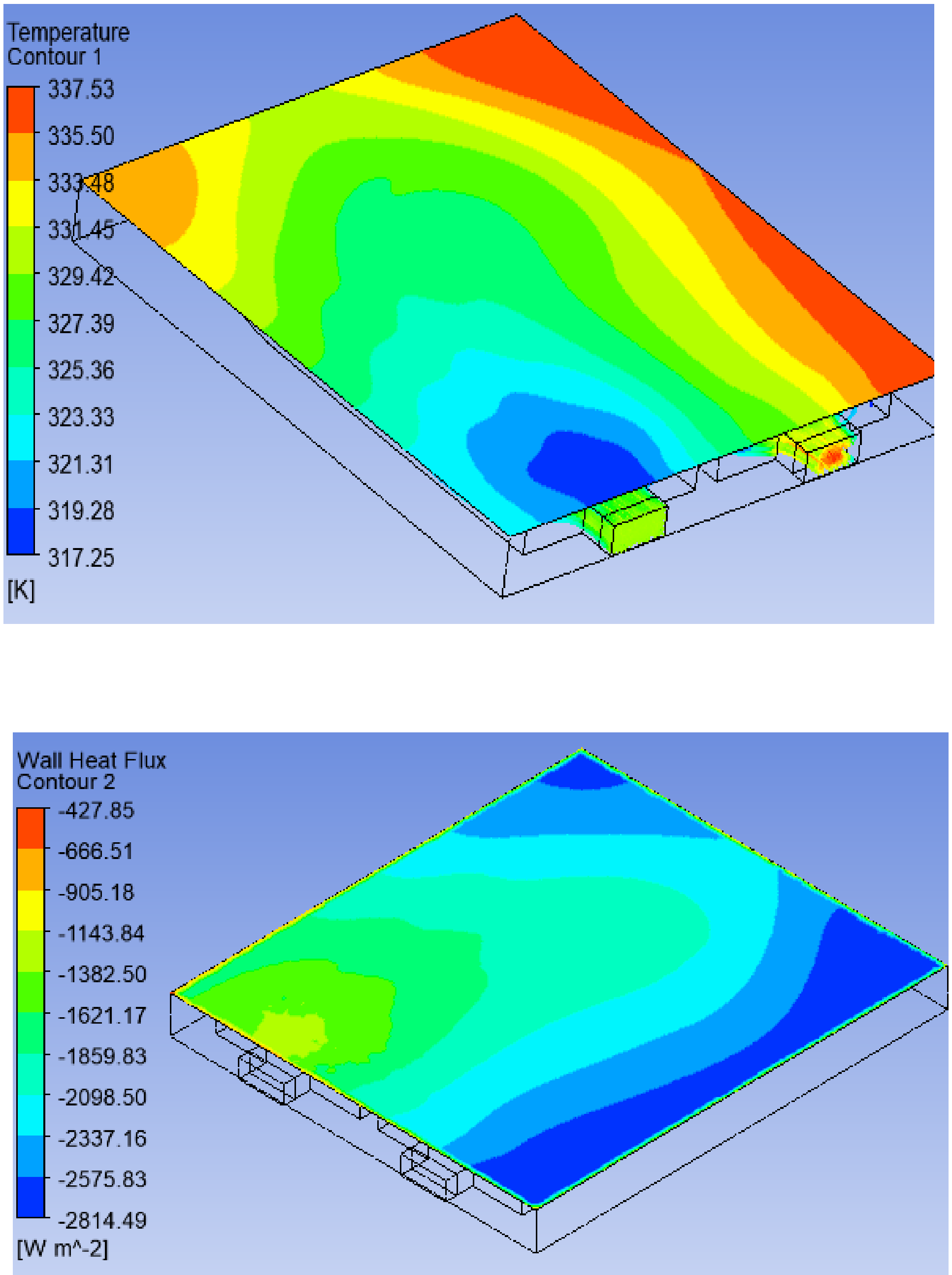



Figure 4.2 Thermal performance of U-shaped microchannel

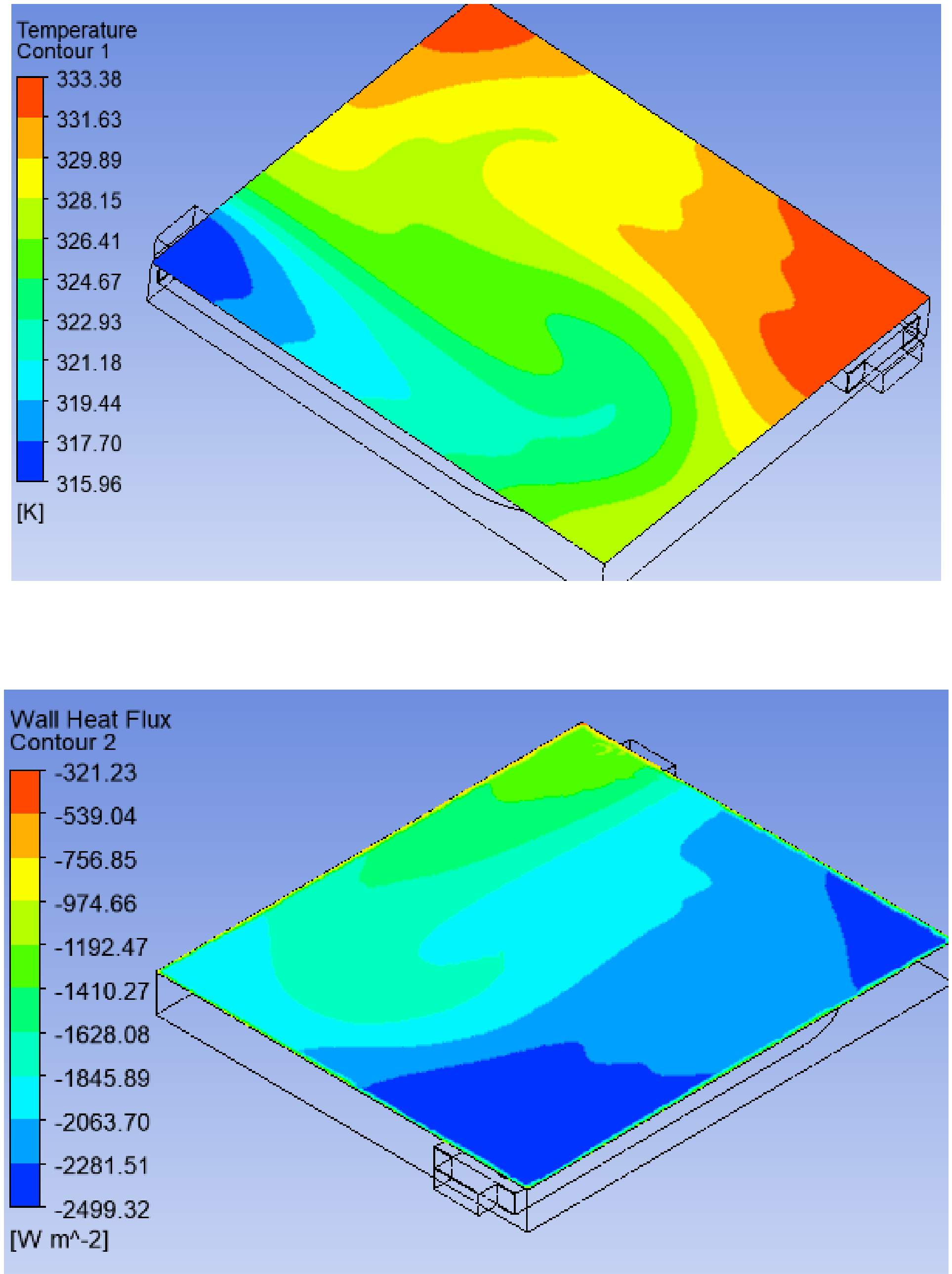
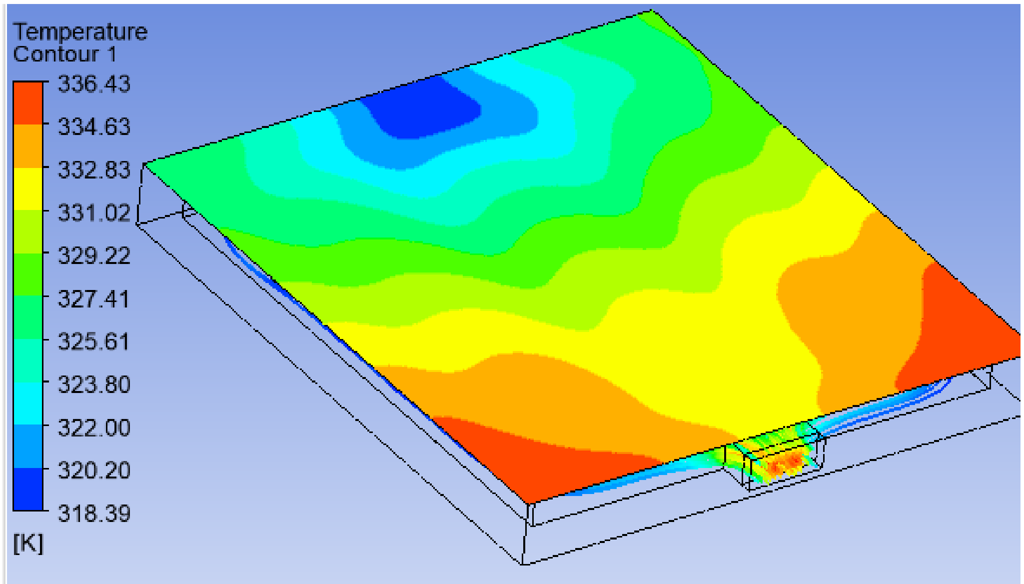



Figure 4.3 Thermal performance of serpentine shaped microchannel



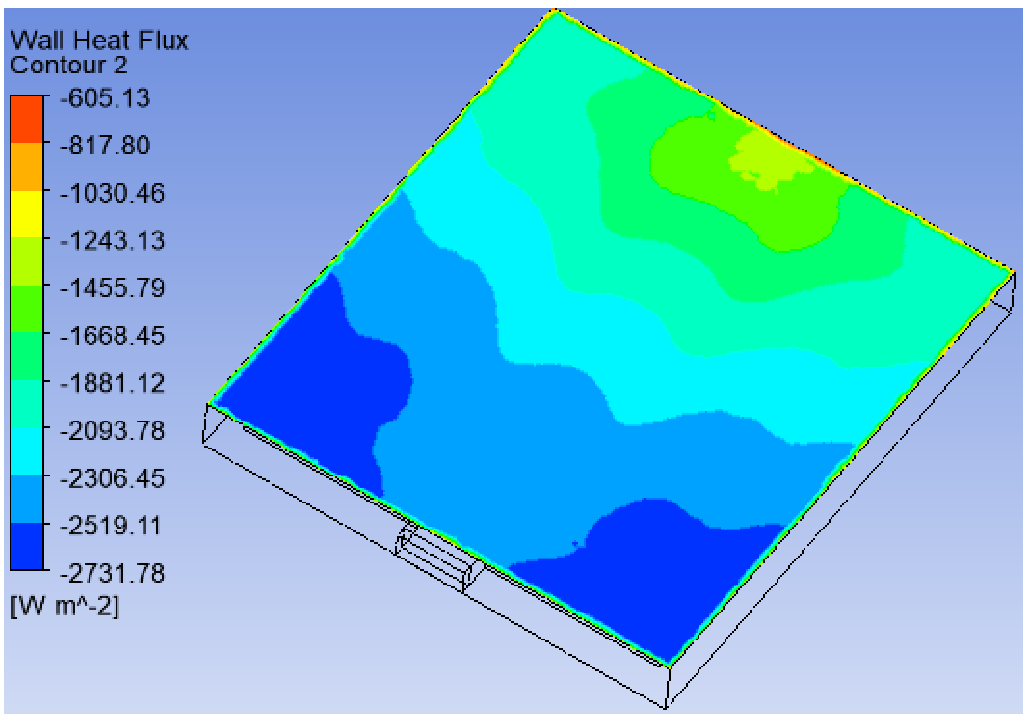
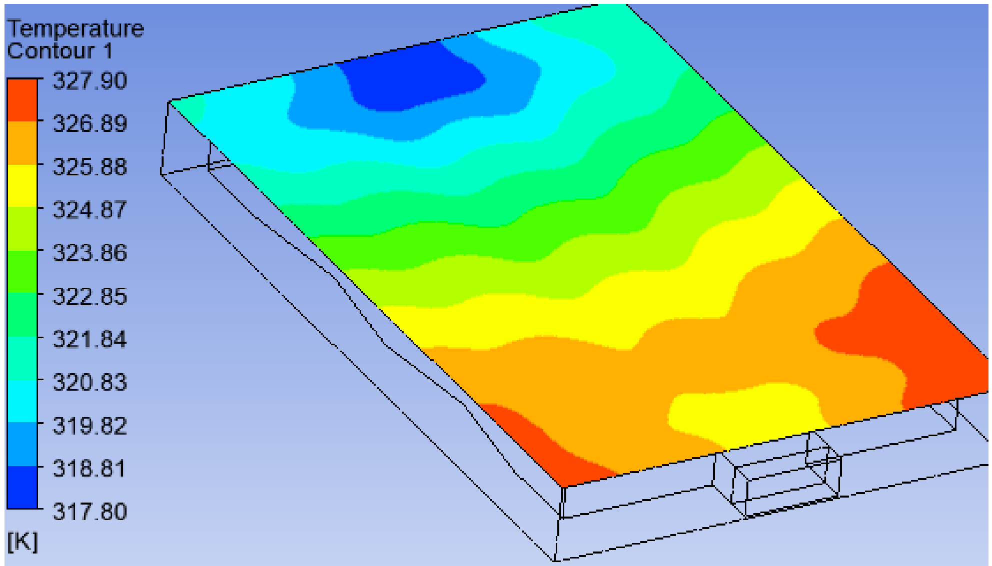




Figure 4.4 Thermal performance of straight microchannel with fins



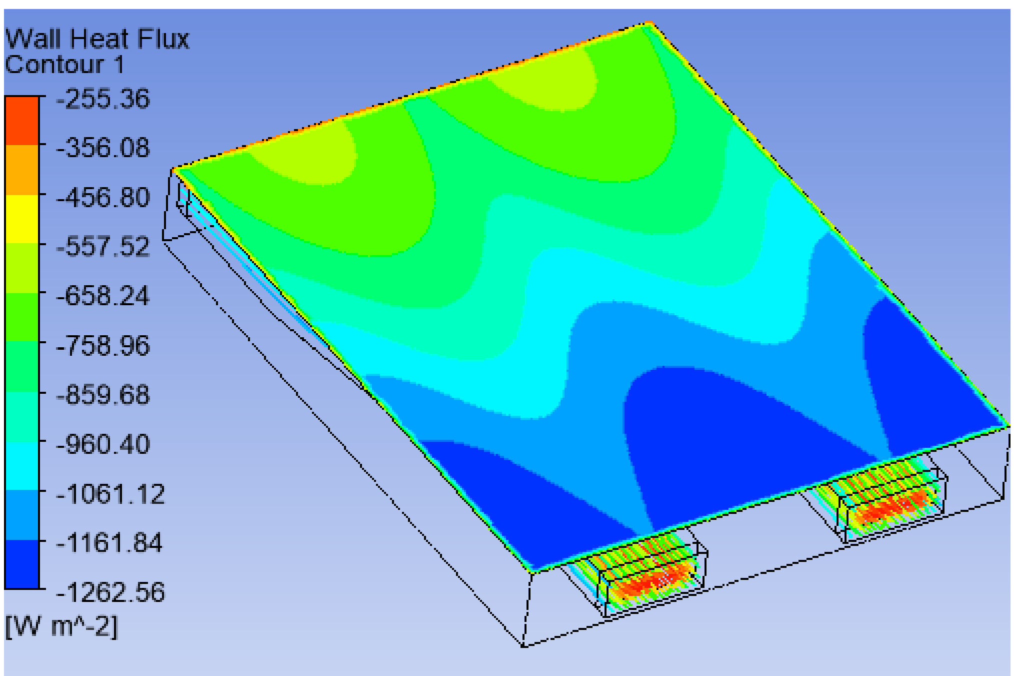
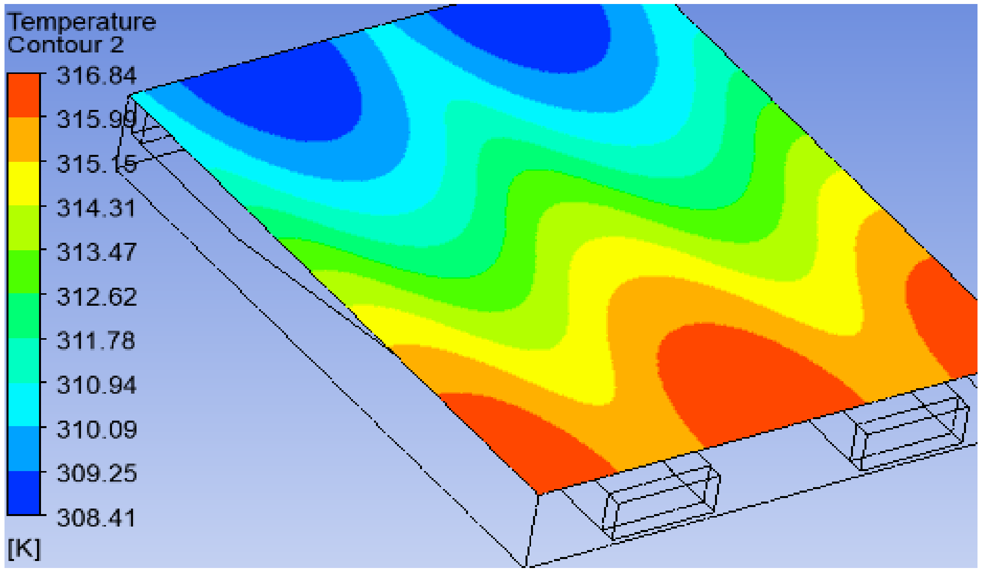




Figure 4.5 Thermal Performance of straight microchannel with varying width



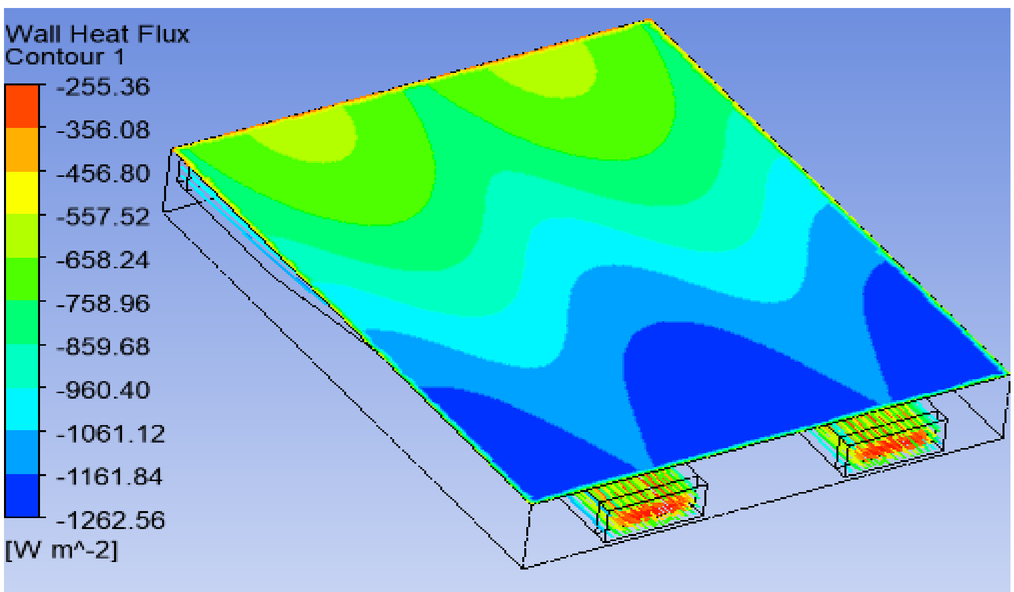
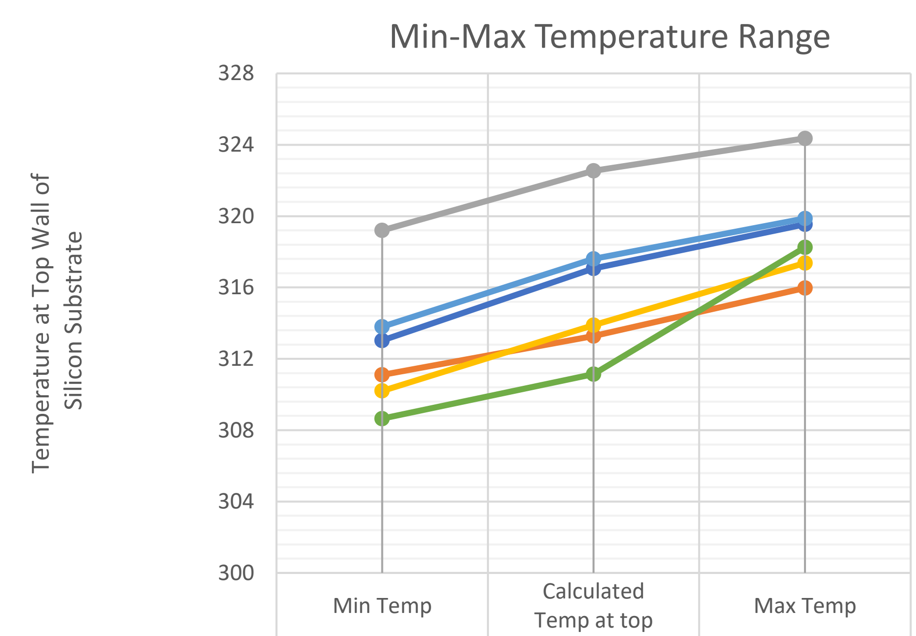




Figure 4.6 Thermal Performance of Straight Microchannel with reduced width

In straight, U-shaped, and serpentine microchannels, the best thermal performance is obtained for serpentine channels, as expected. The results for modifications in the straight microchannels are almost like the serpentine channels. The thermal performance of straight microchannel with reduced width gives the lowest value of temperature and heat flux at the top of the silicon substrate. Hence it could be concluded that microsystems requiring a high thermal performance can be coupled with a straight microchannel with reduced width for better cooling performance.

The temperature obtained at the top surface of the silicon substrate verifies the microchannel effectiveness. The average temperature value at the top of the silicon substrate can be calculated by correlating the convection heat transfer rates with the Heat flux. The graph below shows the min-max temperature range obtained for all types of microchannels having a cross section of 150 x 100 μm$^2$ and subjected to a velocity of 2m/s.




| | Min Temp | Calculated Temp at top | Max Temp |
|---|---|---|---|
| Straight | 313.03 | 317.06 | 319.54 |
| U channel | 311.10 | 313.29 | 315.97 |
| Serpentine | 319.20 | 322.54 | 324.36 |
| Straight with Fins | 310.20 | 313.88 | 317.37 |
| Varied Width | 313.80 | 317.60 | 319.87 |
| Reduced Width | 308.65 | 311.14 | 318.25 |

Figure 4.7 Minimum-Maximum Temperature at the top wall of silicon substrate

The temperature rise of the fluid flowing does not solely depend on the heat flux applied on the bottom but also depends on the viscous dissipation through the microchannel. Viscous dissipation refers to the temperature rise due to the pressure drop in the microchannel. The effect of viscous heating on temperature rise is small for pressure drop ranging between 30 KPa - 150 KPa. Thus, in this research work the temperature at the outlet is considered independent of viscous heating. The contours for the temperature at the outlet for all types of Microchannel are shown below.

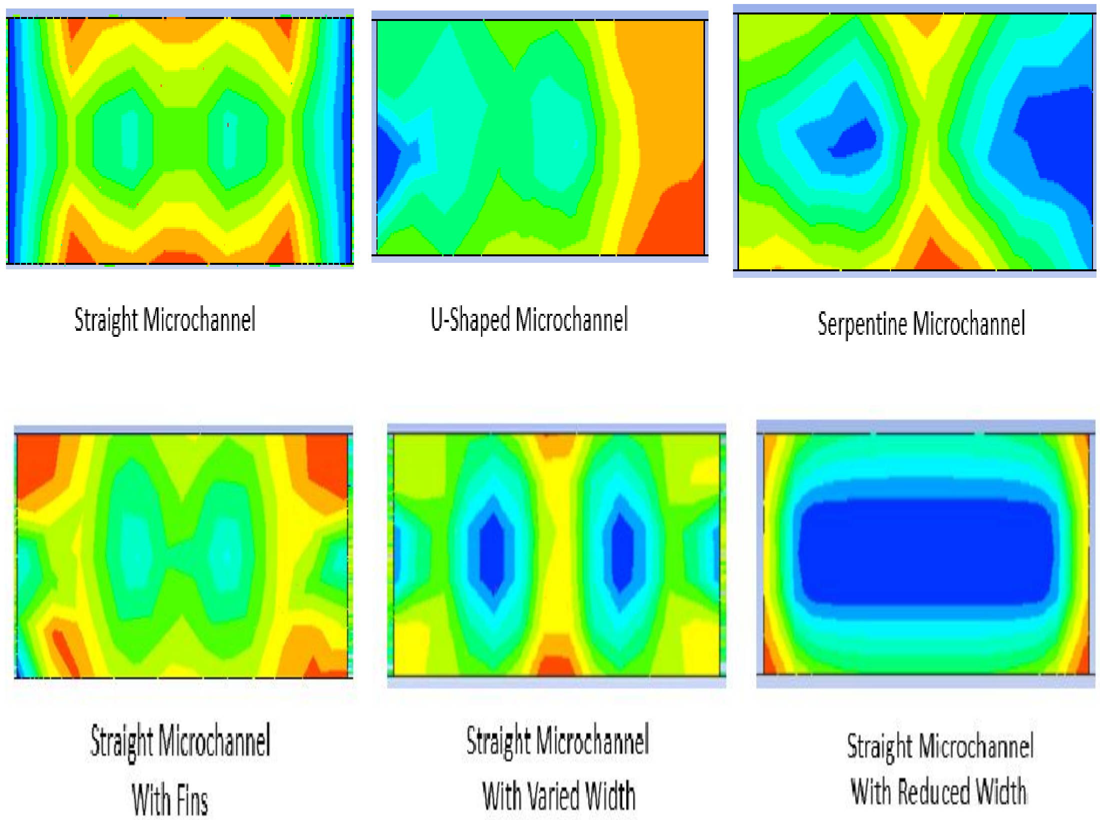
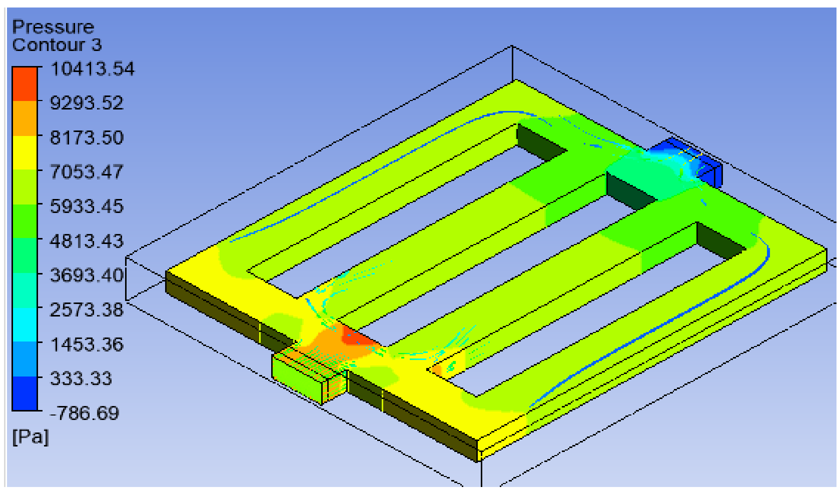
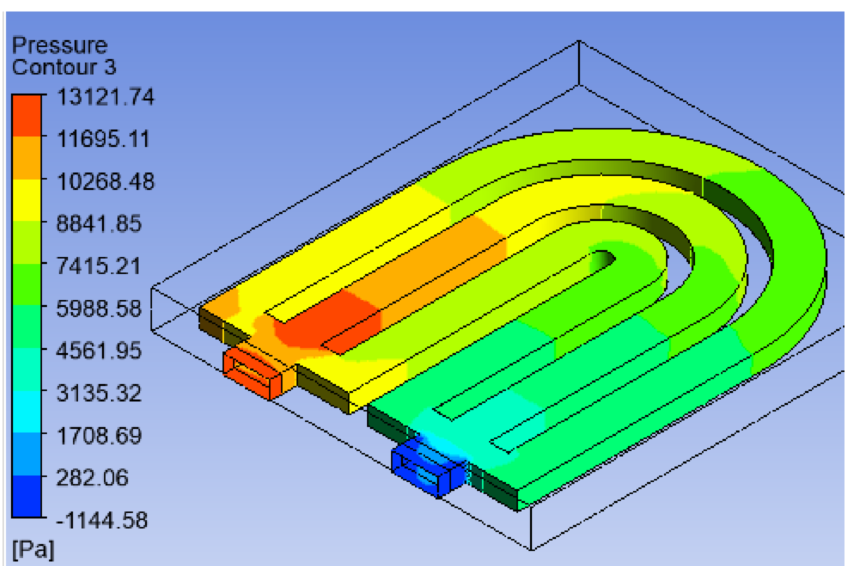


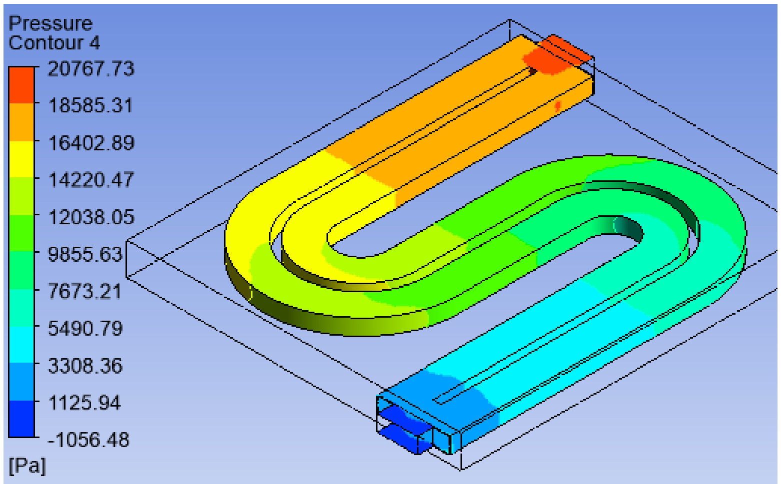

Figure 4.8 Temperature contours for outlet of all microchannels

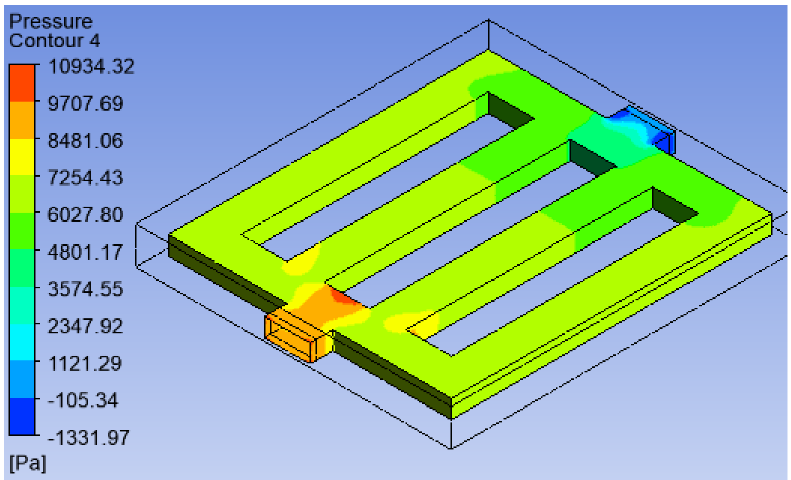
### 4.2 Fluid Performance

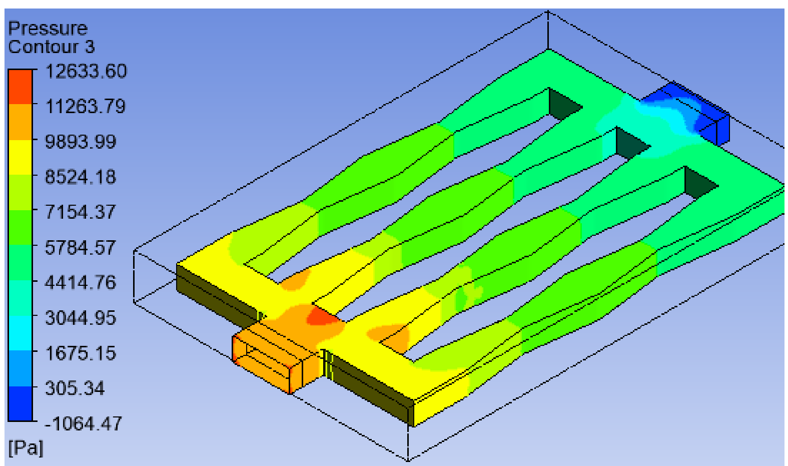
The enhancement in microchannel heat sinks will show better thermal performance as compared to the standard microchannels. But this increase in thermal performance is at the cost of a massive pressure drop. Hence, the pressure drop should also be considered while improving the performance of the systems. The pressure versus length graphs are shown below for a velocity of 2 m/s. Also a combined graph is obtained from ANSYS to compare all the velocities for a single microchannel.




Pressure
Contour 4
20767.73
18585.31
16402.89
14220.47
12038.05
9855.63
7673.21
5490.79
3308.36
1125.94
-1056.48
[Pa]


Pressure
Contour 4
10934.32
9707.69
8481.06
7254.43
6027.80
4801.17
3574.55
2347.92
1121.29
-105.34
-1331.97
[Pa]


Pressure
Contour 3
12633.60
11263.79
9893.99
8524.18
7154.37
5784.57
4414.76
3044.95
1675.15
305.34
-1064.47
[Pa]

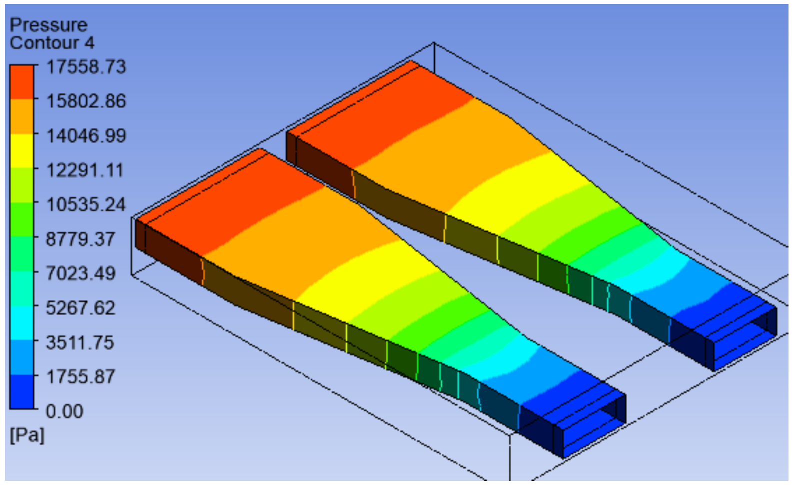



Figure 4.9 Pressure drop for all microchannel at velocity of 2m/s

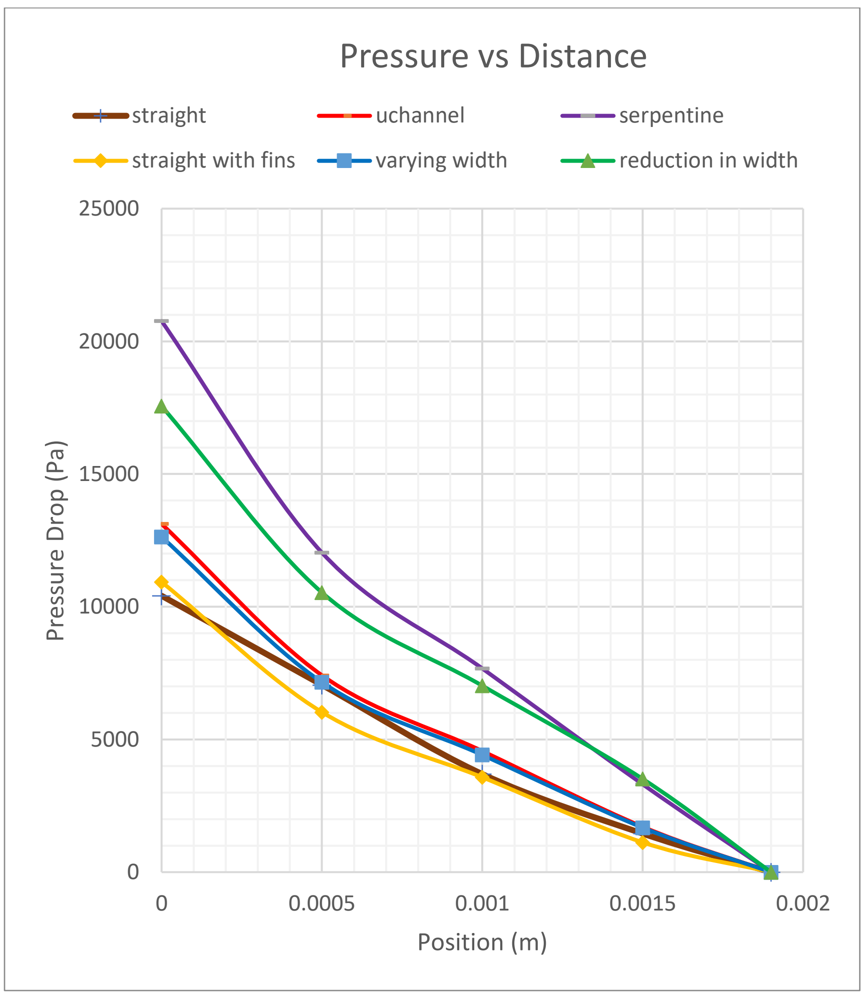



Figure 4.10 Pressure Drop vs Distance for all microchannels at 2 m/s velocity

Channel friction and bends in microchannels are the main cause of the pressure drop in the system. In the basic microchannels, the lowest pressure drop is obtained for straight microchannels, a moderate pressure-drop in U-shaped microchannels, and highest in serpentine microchannels. Hence we can conclude that as the number of bends increases, the pressure drop in the channel increases, as expected.

The modifications in straight microchannels provide better performance than the microchannels with bends, and the best fluid performance is observed for straight microchannels with fins. In varying width and reduced width type of straight microchannels, as the width of microchannel decreases, a larger pressure drop is observed. While increasing the width of microchannels causes a slight rise in pressure or a lesser pressure drop in the microchannel.

In the following figures, Pressure drop and Reynolds number are plotted and compared.

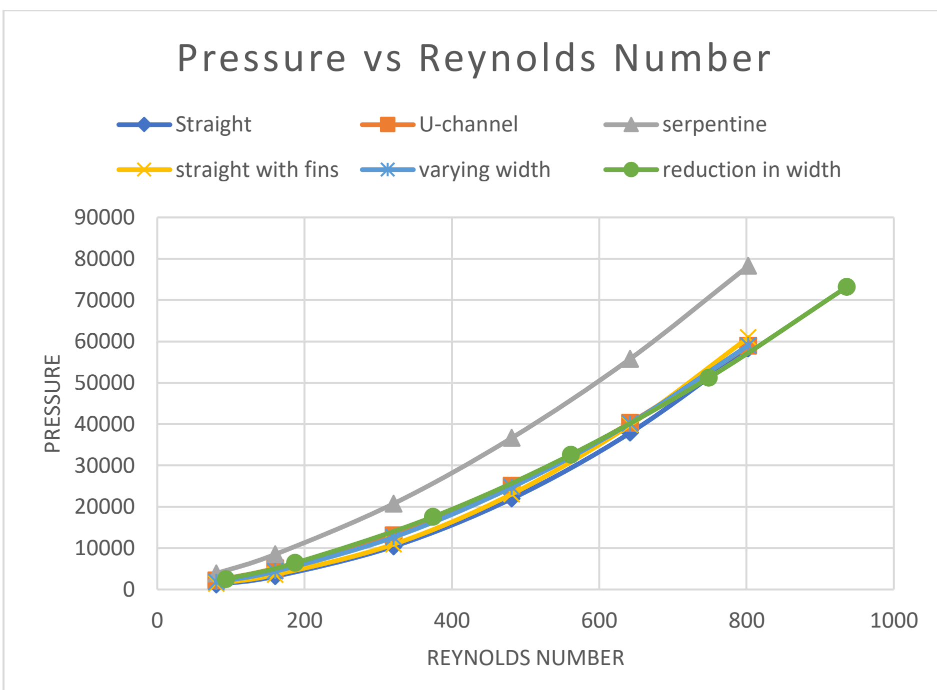



Figure 4.11 Pressure drop vs Reynolds number for all microchannels

The graphs for Pressure versus Reynolds number supports the analytical theory that an increase in Reynolds number causes a increase in pressure drop of the microchannel. The most dominant terms in the Reynolds number are the velocity of the fluid and geometrical properties of the channel. There might be a little uncertainty observed in the fluid velocity, causing an unexpected variation in the pressure versus Reynolds number graph, where with increasing Reynolds number the pressure drop decreases.

In the following figures, the numerical predictions are plotted and compared for the Nusselt number as a function of Reynolds number.

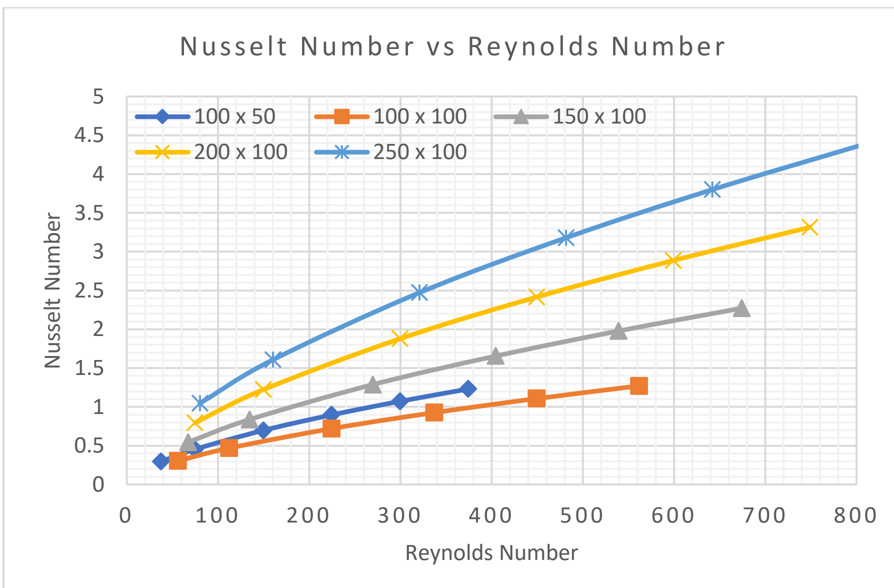



Figure 4.12 Nusselt number vs Reynolds number

Figure 12 explains that as the Reynolds number increases, the Nusselt number also increases, thus it agrees quite well with the analytical theory. If the variation in hydraulic diameter is considered for a single fluid velocity, we can conclude that as hydraulic diameter increases, the Nusselt number increases severely, as expected.

# CHAPTER 5:

# CONCLUSION

This thesis reviews the computationally analyzed results for rectangular microchannels. Conclusions for heat transfer characteristics and fluid flow aspects are obtained and are as follows.

1. Effect of Microchannel Height Variation on Thermal and Fluid Performance

Microchannel height variations are investigated for 100 x 50 μ$m^2$ and 100 x 100 μ$m^2$ cross-sections. Increasing the height of microchannel causes a massive reduction in the overall pressure drop of the channel. Also, the temperature obtained at the top of the silicon substrate is comparatively less. Thus better thermal and fluid performance is obtained for 100 x 100 μ$m^2$.

2. Effect of Microchannel Width Variation on Thermal and Fluid Performance

100 x 100 μ$m^2$ and 150 x 100 μ$m^2$ cross-sectional microchannels are investigated for width variations. There is a slight reduction in the pressure drop of the channel with an increased width. Lower values of temperature at the top of the silicon substrate are obtained. The overall effect on cooling performance has smaller effect as compared to height reductions.

3. Effect of Velocity Variation on Thermal and Fluid Performance

An investigation is conducted for Microchannel heat sinks with velocities between 0.5 and 5 m/s. The pressure drop in the microchannel increases with an increase in fluid flow velocity. But, there is a significant drop in the temperature obtained at the top of the silicon substrate. Thus Pressure drop is to be taken into consideration while selecting the fluid velocity. In the research conducted, fluid with 2 m/s velocity has an optimized effect on the thermal and fluid performance of the Microchannel.

4. Comparison of Straight, U-shaped and Serpentine Microchannel

Microchannels with bends show huge pressure drops than the straight microchannels. Thus straight microchannel has better fluid performance. The value of temperature at the top of the silicon substrate is almost equal for all the microchannels. But as compared to others, the U-shaped microchannel has the best thermal performance, if all the varying parameters are kept constant. Depending on the design requirement of microsystems, straight or U-shaped microchannels can be selected accordingly.

5. Effectiveness of Modification in Straight Microchannel

Straight microchannel with fins has better thermal and fluid performance than straight microchannel with varied width. For Straight Microchannel with fins, the temperature at the top of the silicon substrate is comparatively less, but the pressure drop obtained is slightly more than the regular straight microchannels. Also straight microchannels with reduction in width provide the best thermal performance, but the Pressure drop is massive. Hence, if better thermal performance is allowed over a slightly higher pressure drop, we can implement fins in regular straight microchannels, keeping all the varying parameters constant.

# CHAPTER 6:

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