

Heat Transfer Characteristics of Water Cooled Minichannel Heat Sink Using Different Fluid Flow Geometries

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Abstract: Efficient heat transfer for compact electronic components has become a major need in these days. For this purpose, we require a minichannel heat sink with a liquid cooling system that makes these requirements as possible. In this work, both analytical and CFD investigations have been carried out to calculate the heat transfer performance of a minichannel heat sink consisting of cross sections with three different shapes of a rectangular, trapezoidal and hexagonal in which working fluid is made to flow. The simulation is conducted with water as the working fluid for three different shapes with Reynolds number ranging from 200 to 1000 and analyzed numerically for the single-phase laminar flow with the boundary condition of constant heat flux. The channel dimensions and inlet velocity effects on the Nusselt number, pressure drop, and heat transfer coefficient are studied. The 3D steady-state, laminar flow, and governing equations of heat transfer are solved using the finite volume method by commercial ICEM-Fluent software.

Keywords: Computational fluid dynamics, Heat transfer, Minichannel heat sink, ICEM-Fluent CFD.

1. Introduction

In the present years of modernization and due to the technology advancement, the need of liquid cooling in various compact electronic devices and other electrical devices has been a major area of concern. The heat generated by electronic circuits must be dissipated out of the system so we require different cooling systems for these devices to work properly and effectively. Since the last few years minichannel cooling system has been a subject of research. The amount of work on the effect of heat transfer on flow geometries in mini/microchannels is fast and growing. Many researchers have emerged with a different cross section of the mini/microchannel but for sure there is an effect of the configuration of these channels on heat transfer coefficient, Nusselt number, and Reynold number. The main advantage of using mini/microchannel is to achieve a high heat dissipation rate in a smaller space. It has been proved that single-phase, laminar flow, and forced convection in minichannels is one of the effective cooling ways in a variety of applications.

The microchannel heat sink was first developed and proposed by Tuckerman and Pease [1] in 1981. For VLSI circuits, an investigation has been done by authors with a high performance heat sink. Designed and tested water cooled based silicon minichannel heat sink used for integrated circuits. They also stated that reducing the dimension to the micro scale of a liquid cooling heat sink is helping in enhancing the performance of heat transfer. The experimental investigation and numerical analysis are presented by Lee et al. [2] to explore the validity of the classical correlations for analyzing the thermal behavior in single phase rectangular microchannels that are based on conventional sized channels. The microchannel is made up of copper and de-ionized water was used for the experiment and the Reynolds number was ranging from 300 to 3500. Numerical predictions those obtained were based upon the continuum and classical approach. Those predictions were found in an appropriate agreement with the data showing an average deviation of 5%. Qu and Mudawar [3] an experimental and numerical investigation is carried out for characteristics of heat transfer and pressure drop of oxygen free copper made heat sink and deionized water as the working fluid. The microchannel was studied for a rectangular array with a hydraulic diameter of 231 μ m and 713 μ m. The numerical investigation and effect of parameters of geometries on water flow and characteristics of heat transfer are studied with three different geometry shapes (Rectangle, Trapezoidal, and Triangle) and heat flux is added to the top plate of the aluminum microchannel. The results show that with an increase in heat flux pressure drop decreases from the top plate of the heat sink for the same Reynolds number. Further, they studied different flow paths such as step, curvature, and zigzag, etc. Results stated that for microchannel with



equal cross section, zigzag microchannel was having a high coefficient of heat transfer among all channel shapes [4, 5].

There was a study of comparison between circular and square microchannel with ammonia as a coolant for optimization of the thermal performance by using a genetic algorithm. Ghazali-Mohd et al. [6] reported that for circular channels thermal resistance is lower by 21% and 35% at the lowest and highest pumping power than square microchannel. Circular geometry performed better thermally and hydrodynamically. Chai and Tassou [7] investigated the effect of cross-section geometries to predict the heat transfer and pressure drop characteristics of supercritical CO_2 working fluid in minichannels. They presented six geometries with a cross-section of a square, semicircle, circle, equilateral triangle, ellipse, and rectangle with the same hydraulic diameter of 1.22mm. The numerical results show that the highest heat transfer coefficient in circle and ellipse as compared to other geometries. Thermal performance and hydraulic parameters were studied by Ghasemi et al. [8] with the experimental investigation. The heat sink is fabricated with aluminum material with four minichannels of circular cross sections with three different values of hydraulic diameter. The lower thermal resistance was shown by 4mm hydraulic diameter than 6mm and 8mm hydraulic diameter. Kewalramani et al. [9] reported an empirical correlation for laminar flow with forced convection in the trapezoidal microchannel. The experimental study and numerical model were developed for trapezoidal geometries with side angles of 30° and 60° with an aspect ratio in the range of 0.1 to 10 to carry out the poiseuille number and Nusselt number. Su et al. [10] studied, the numerical investigation of the elliptical minichannel heat sink and purposed a general correlation for the first time for the apparent friction coefficients and entrance length for the elliptical channel. They have examined the Reynolds number effects and aspect ratio on friction coefficient, entrance length, and Nusselt number in detail. The Reynolds number ranging from 14-450 for minichannel for enhancement of heat transfer and pressure drop was experimentally investigated by Moghanlou et al [11]. There are accuracies of 17%, 8%, and 14% were observed for thermal resistance, Nusselt number, and friction factor respectively. The experimentation is done on a square configuration with a heater fixed in its bottom.

From the literature review, it can be concluded that many kinds of researches have been focused on changing the cross-sectional shapes of fluid flow geometry and its configuration of minichannels. Furthermore, a small amount of work has been focused on investigating the heat transfer characteristics and the effect of geometrical parameters on the cooling performance, particularly for trapezoidal and hexagonal shapes. In this study, both analytical and CFD investigation is to be carried out to calculate the heat transfer performance of minichannel heat sink with water as working fluid for three different geometrical configurations (Rectangular, Trapezoidal, and Hexagonal) & compare the heat transfer performance of three different cross-sectional shapes and the decision is made for optimum geometry which a gives a better cooling performance.

2. Physical Model

The rectangular CAD model of the minichannel is shown in Figure 1. All minichannel heat sinks having a base size of 26.9 mm x 50 mm and a total depth of 6 mm. The dimensions of the rectangular shape are taken from Ho et al. [12]. The desired model of the heat sink consists of rectangular, trapezoidal, and hexagonal cross-sections in which working fluid is made to flow which is shown in Figure 2. There is a total of 8 parallel channels in each heat sink and the top surface is assumed to be covered with insulating material to prevent splashing.

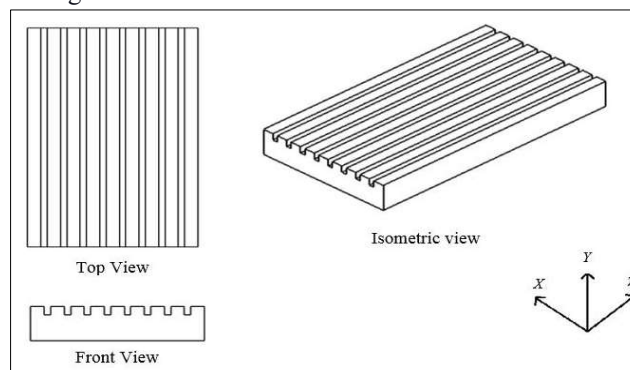


Figure 1. CAD model of rectangular minichannel heat sink

Dimensions of trapezoidal and hexagonal shapes are calculated, such that all geometries are designed by keeping hydraulic diameter and surface area as constant. In this study, all factors like fluid type, flow type, and governing equation did not change and only geometries of fluid flow were changed. The small hydraulic diameter of a minichannel can lead to appreciable heat dissipation, which is desirable in electronic systems. Therefore, a strong understanding of the heat transfer rate, Reynolds number, heat transfer coefficient, Nusselt number, flow rate, and velocity change has more importance in the design of minichannel. The detailed dimensions of the models are given in table 1.

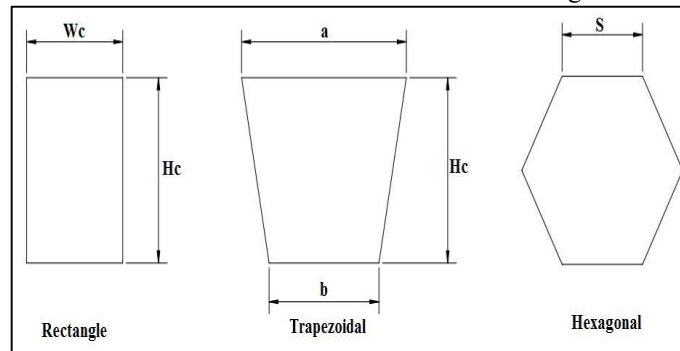


Figure 2. Different types of geometrical

Table 1. Dimensions of fluid flow geometries

Names of geometry	Dimensions
Rectangular	$W_c=1.0\text{mm}$, $H_c=1.5\text{mm}$, $D_h=1.2\text{mm}$
Trapezoidal	$a=1.4\text{mm}$, $b=0.8\text{mm}$, $H_c=1.5\text{mm}$, $D_h=1.2\text{mm}$
Hexagonal	$S=0.7\text{mm}$, $D_h=1.2\text{mm}$

3. The Computational Domain

In the present study, a 3D convective heat transfer simulation of the minichannel heat sink was carried out. The heat sink was made up of copper material and water as the working fluid was considered in the simulation. The following assumptions were made while modeling minichannel heat sink for analyzing cooling performance.

- (1) Both heat transfer and fluid flow are in steady state and three dimensional.
- (2) Fluid is incompressible, single phase, and the flow is fully developed laminar flow.
- (3) The fluid thermo-physical properties are constant, negligible viscous dissipation, and negligible radioactive.
- (4) The effect of body forces are neglected.
- (5) All minichannel are supposed to be equal in heat transfer so one channel can be chosen for numerical simulation, the computational domain is used which is shown in Fig. 3. This problem is converted into symmetric boundary conditions it includes fluid flow channel height, width, and solid wall thickness which is equal to half of the thickness between two channels.

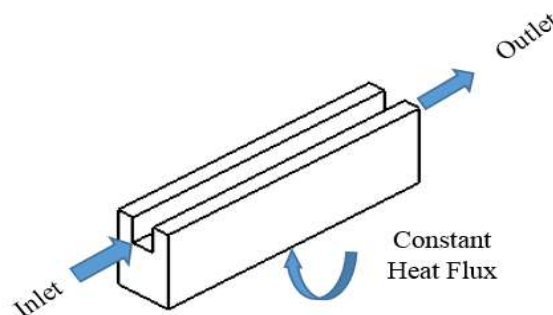


Figure 3. Computational domain of single channel

4. Grid Independence Study & Boundary Conditions

After generating the computational model, the meshing of the model is done on the ICEM CFD module in ANSYS software. The meshed model of rectangular, trapezoidal, and hexagonal minichannel heat sinks are shown in below Figure. 4. The fluid domain and solid domain has meshed with the same mesh density. The discretization has been done with Tetra/Mixed elements using the GSF method. Global scale factor (GSF) is one of the meshing types and is defined as the ratio of maximum length to the minimum length of an element in geometry. The grid independence test was conducted by adopting six different global scale factors of 3, 3.25, 3.5, 3.75, 4, and 4.25 to maintain the accuracy of the calculations and it is observed that the last two mesh models are given less pressure loss difference with a variation of 2%. Thus, the global scale factor (GSF) 4 mesh is adopted for this simulation. The same grid sensitivity approach was used for all cases in the present study. If we increased mesh density the simulation show less than 0.1% variation in pressure drop.

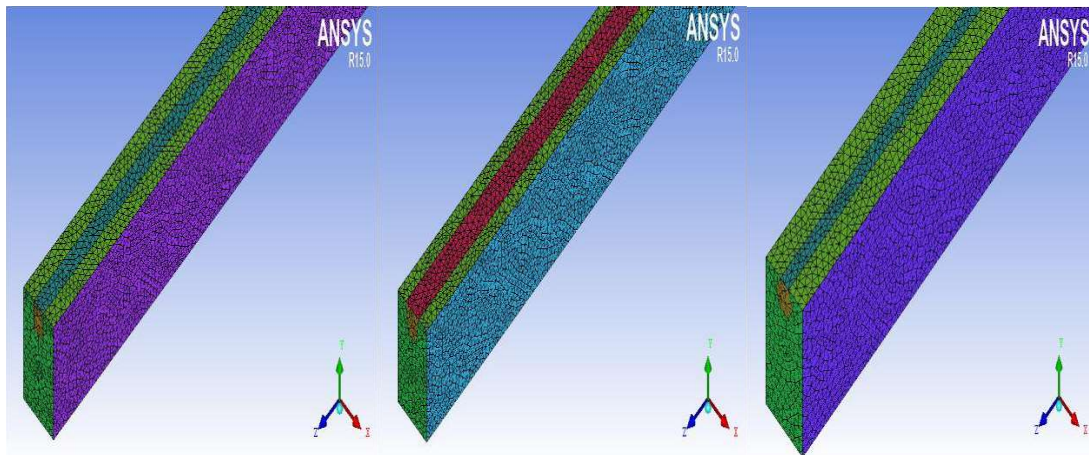


Figure 4. Meshed Geometries

Table 2. Meshing Parameters

Types of minichannel	Number of elements	Number of nodes
Rectangular minichannel	275353	46524
Trapezoidal minichannel	275486	46513
Hexagonal minichannel	269255	45491

The heat transfer performance of rectangular minichannel is compared with the trapezoidal and hexagonal minichannel heat sink, which has the same hydraulic diameter. The discretization of the domain and the governing equations are calculated by finite volume method and by using the SIMPLE algorithm these governing equations are solved with pressure-velocity coupling. The second-order upwind scheme is applied for all the variables and a pressure-based solver is used for numerical simulation.

The following boundary conditions are assumed for the present study:

1. The inlet temperature of water is 300K.
2. The inlet velocity is calculated from Reynolds number. For Re number 200, 400, 600, 800, 1000 the velocities are 0.167m/s, 0.334m/s, 0.501m/s, 0.664m/s & 0.884m/s respectively.
3. The constant heat flux is added to the bottom surface of the minichannel which is 32000W/m².
4. The outlets are set as pressure outlets which is at zero gauge pressure.
5. The remaining side walls were considered as adiabatic walls.

Various physical models are applied for carrying out CFD simulations of minichannel for three different cross-sections. As the Reynolds number of working fluid is found to be in the laminar zone. So, a viscous laminar flow modeling scheme is used for carrying out CFD simulation. In, order to study the temperature distribution, the energy model is turned on. Due to which temperature of the working fluid is specified.

5. Data Reduction from CFD Results

The water entered from the inlet of minichannel and convective heat transfer takes place in the system in which working fluid is absorbed heat from the heat sink and water leave through the outlet of the heat sink. So, heat is removed by circulating water through the heat sink. After boundary condition is applied to the computational model and the results obtained from that is taken to the CFD post software for the post-processing process. In CFD post software, the temperature and pressure variations are obtained by plotting straight line axis in both solid and fluid domain and data were collected. The line was created at mid of fluid domain and on the solid base of the heat sink.

1. The average temperature of fluid is calculated as,

$$(T_f)_{avg} = (T_{fi} + T_{fo})/2 \quad K$$

2. The temperature between solid base average temperature and fluid average temperature is calculated as,

$$\Delta T = [(T_w)_{avg} - (T_f)_{avg}] \quad K$$

3. Mass flow rate of working fluid is calculated as,

$$\dot{m} = \rho A_{cs} V \quad m/s$$

4. Heat transfer from inlet to outlet is calculated as,

$$Q = \dot{m} c_p (\Delta T)_f \quad \text{Watt}$$

$$\text{Where, } (\Delta T)_f = T_{fi} - T_{fo} \quad K$$

5. Heat gained by water through convection is same as that of heat transfer through convection heat transfer.

$$Q = \dot{m} c_p (\Delta T)_f = h A_s \Delta T \quad \text{Watt}$$

6. The average heat transfer coefficient is calculated as,

$$h = Q / A_s \Delta T \quad W/m^2K$$

7. Nusselt number is obtained by below equation,

$$Nu = h D_h / K_w$$

8. Reynolds number is calculated as,

$$Re = \rho V D_h / \mu$$

9. The hydraulic diameter is calculated from below equation,

$$D_h = 4 A_{cs} / P$$

6. Results & Discussions

In this study, the phenomena of liquid cooling in the minichannels based heat sink have been studied. For this purpose, a copper heat sink has been selected having three different cross-sectional shapes and water has been taken as a coolant for the cooling system. The main objective of this study is to analyze and evaluate the heat transfer parameters like Nusselt number, heat transfer coefficient, and pressure drop of the heat sinks and to compare the heat transfer performance of the heat sinks with each other.

6.1 Validation of numerical approach

Table 3. Validation Results

Re	CFD Results ΔP (Pa)	Analytical Results ΔP (Pa)	Difference (%)
200	184.19	170.82	7.25
400	372.96	341.91	8.32
600	598.24	512.87	14.27
800	805.87	683.83	15.10
1000	1052.89	854.68	18.82

The numerical results are validated through the analytical solution method. Co-relations given by Khandlikar [13] are used to predict pressure drop (ΔP) in fully developed laminar flow across a straight rectangular channel which is shown in table 3. From the above table, it is shown that CFD results and analytical results are matching with some eligible error difference and there is a total average deviation of 12.75% in the analytical result and the numerical result of a pressure drop.

Figure. 5. represents the comparative analysis on the performance of minichannel based heat sinks and variation in the Nusselt number employing at different Reynolds numbers. It can be observed that as the Reynolds number increases Nusselt number also increases because the thermal boundary layer thickness decreases with an increase in fluid velocity. It is seen that the Nusselt number is higher for the rectangular shape among trapezoidal and hexagonal. The Nusselt Number results obtained for rectangular parallel minichannel is matched with the results obtained by Ho et al. [12] with a maximum error of 2%. Figure. 6. Represents the comparative analysis of the three different minichannel heat sink and it is clear that the value of the heat transfer coefficient goes on increasing with an increase in the value of Reynolds Number as the inlet velocity of the working fluid increases. It is seen from the figure that the value of the heat transfer coefficient for the rectangular shape is higher as compared to the remaining two shapes. The hexagonal shape showed the lower values of the coefficient of heat transfer.

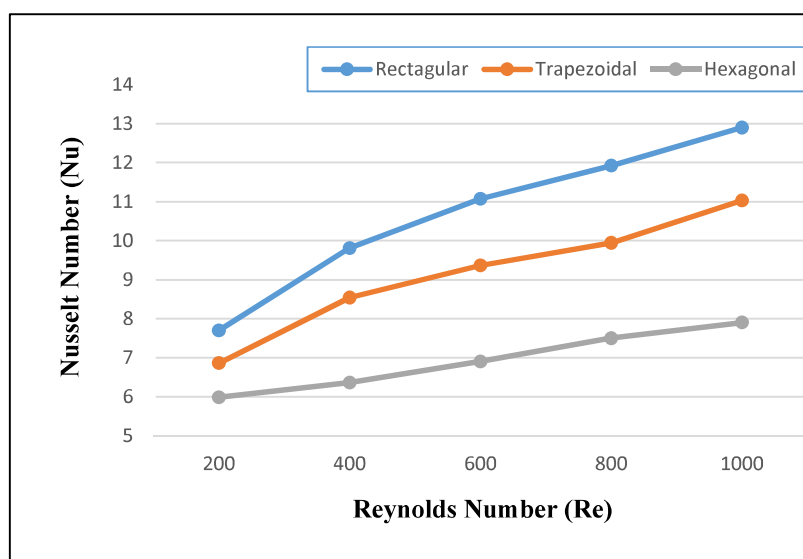


Figure 5. Nusselt number variation with respect to Reynolds number

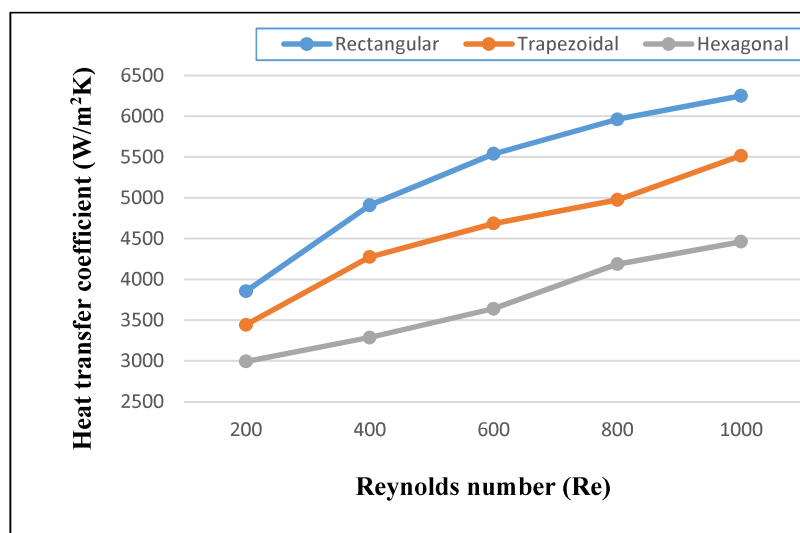


Figure 6. Variation of heat transfer of coefficient with respect to Reynolds number

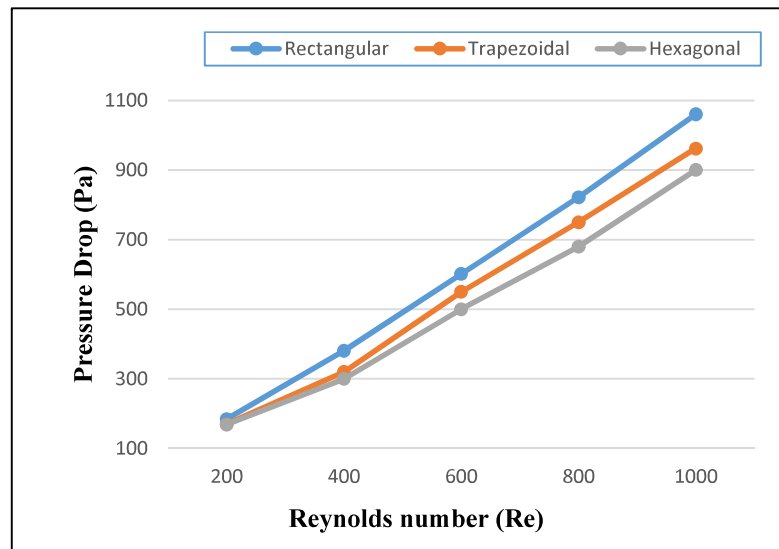


Figure 7. Variation of Pressure drop with respect to Reynolds number

Figure. 7. Shows the variation of pressure drop at Reynolds number 200-1000. From these figures, it is clear that the value of pressure drop goes on increasing with the increase in the value of the Reynolds number. While the hexagonal shape has the lowest pressure drop and the rectangular shape have the highest pressure drop compared to the trapezoidal shape. It should be noted that the fluid path in the numerical simulation, the pipes, and fittings effects between pressure transducer which are present in the experimental analysis are not included in the simulation.

6.2 Temperature Variations

CFD simulated temperature results of minichannel of three different cross-sectional shapes will give an idea about the heat transfer phenomenon in detail. From temperature contours, the temperature distribution of working fluid is shown, from inlet to outlet. It also illustrates how working fluid is picking up, and thereby help in cooling of the minichannel. It has also shown that for a working fluid and at the same flow rate, minichannel of rectangular-shaped has shown better heat transfer as compared to among other shapes. As more heat is picked up by the working fluid, which is apparent from the greater rise in temperature as compared to the inlet. All the below represented figures are taken when the Reynolds no. is 200.

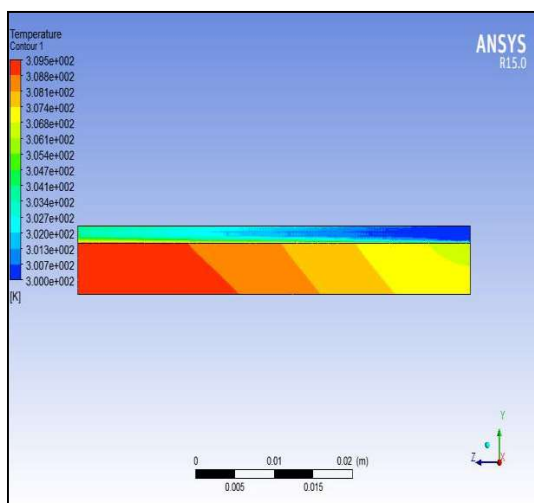


Figure 8. Temperature contour of rectangular minichannel heat sink

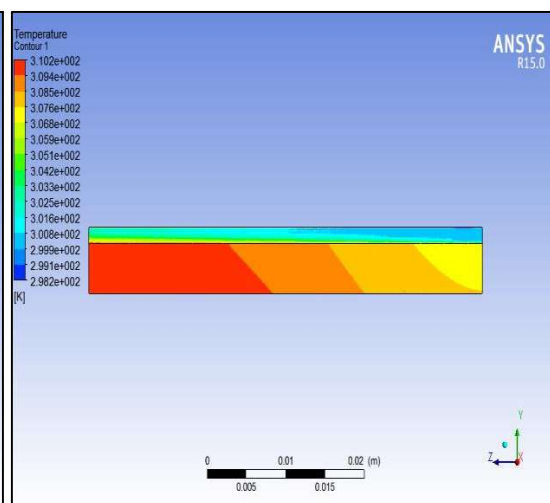


Figure 9. Temperature contour of trapezoidal minichannel heat sink

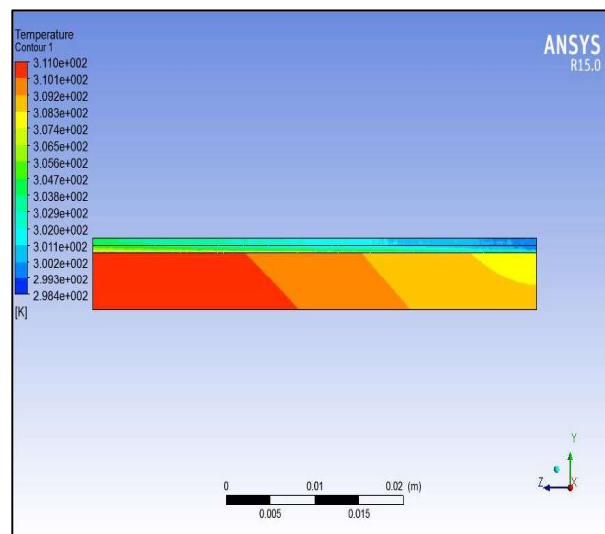


Figure 10. Temperature contour of hexagonal minichannel heat sink

6.3. Pressure Variations

The pressure variations of three geometrical configurations of minichannel will give an idea about the fluid flow structure in detail. Below are the pressure contours of three geometries which are showing the pressure distribution of heat sink from inlet to outlet along the length. All the below represented figures are taken when the Reynolds no. is 200

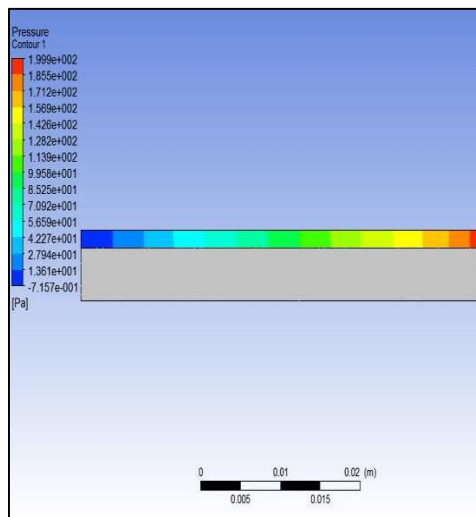


Figure 11. Pressure contour rectangular minichannel heat sink

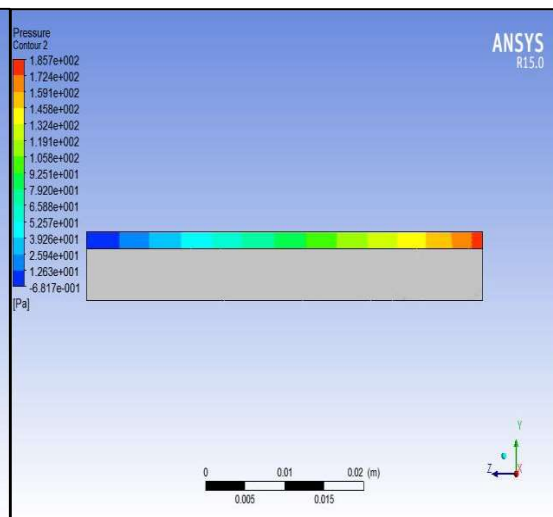


Figure 12. Pressure contour of trapezoidal minichannel heat sink

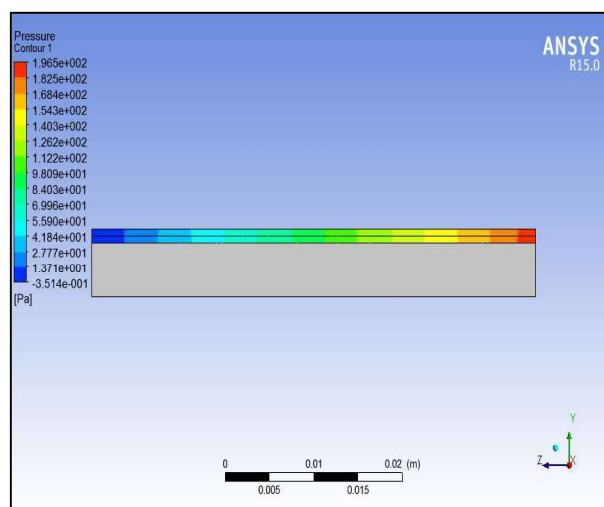


Figure 13. Pressure contour of hexagonal minichannel heat sink

7. Conclusion

In the present work, ICEM-FLUENT CFD (ver. 15.0) software is used for calculating heat transfer performance of minichannel heat sink for different flow rates or Reynolds number.

- 1) Rectangular shaped cross-section of the minichannel has shown better cooling performance as compared to the trapezoidal and hexagonal cross-section of minichannel with the same working fluid and at the same flow rate.
- 2) The thermal performance of rectangular shape is a 14% and 32.12% increase in heat transfer rate as compared to the trapezoidal and hexagonal shapes respectively.
- 3) The average heat transfer coefficient of rectangular, trapezoidal, and hexagonal shapes are 5301.83 W/m²K, 4577.32 W/m²K, and 3711.82 W/m²K respectively. This shows that the heat transfer coefficient is higher for rectangular shape and there is a 13.66% and 29.98% increase in heat transfer coefficient as compared to trapezoidal and hexagonal shapes respectively.
- 4) An increment in pressure drop is seen, with a corresponding increase in the Reynolds number. Higher values of pressure drop are seen in rectangular minichannel and least in hexagonal minichannel. While the trapezoidal minichannel is in between rectangular and hexagonal minichannel.

8. References

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NOMENCLATURE

A_{cs}	Channel flow area, m ²
A_s	Channel surface area, m ²
a	Channel width of trapezoidal, mm
b	Bottom channel width of trapezoidal, mm
S	Hexagonal side length, mm
C_p	Specific heat at constant pressure, J/Kg K
D_h	Hydraulic diameter, mm
h	Convective heat transfer coefficient, W/m ² K
K	Thermal conductivity of water, W/m.K
V	Fluid velocity, m/s
L_c	Length of channel, mm
P	Channel perimeter, mm
\dot{m}	Mass flow rate of cooling water, kg/s
N	Number of parallel minichannels
q''	Heat flux, W/m ²
$(T_f)_{avg}$	Average Mean temperature of fluid, K

$(T_w)_{avg}$	Temperature of solid wall, K
T_{fi}	Inlet temperature, K
T_{fo}	Outlet temperature, K
Nu	Nusselt number
Re	Reynolds number
Q	Heat rate, W

Greek symbol

ρ	Density of water, kg/m ³
μ	Dynamic viscosity, N s/m ²
Δp	Pressure drop, Pa