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Numerical Study of Different Cross-Sectional Stacked Microchannel Heat Sink

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***Abstract*— the heat extraction problem is becoming an important factor in the development of micro-electronics. The microchannel heat sink is designed for electronic chips that could be effectively cooled by means of forced convection, by water flowing through the microchannels. This paper presents a Computational Fluid Dynamics (CFD) flow simulation modeling, where water is made to flow across different cross-sectional microchannel heat sinks placed on heat source. The flow simulation of water and convective heat transfer are carried by using commercial software "SOLID WORKS FLOW SIMULATION". In the CFD process stacked microchannels of various cross-sections viz., rectangular, triangular, pentagonal and circular are designed, then by defining the computational domain, boundary conditions as inlet mass flow (1e-5 kg/s),outlet pressure (static pressure) and heat flux(750w/cm^2) and by considering the parallel and counter flow direction of water in different cross-sectional microchannels the temperature drop in heat sink, pressure drop across the channels and amount of volumetric heat transfer coefficient are analyzed and compared.**

Keywords*— *Microchannel, Heat sink, Heat flux, mass flow rate, computational domain.

1. INTRODUCTION

Thermal management of components is the most important consideration for electronic cooling. The microchannel heat sinks have been developed by many researchers in recent years. Numerous literatures have been published on fluid flow and heat transfer characteristics of microchannels.

Tuckerman and Pease [1] have demonstrated a heat sink with microchannels. In this research they found that microchannel heat sinks can extract more heat and are preferred for chip cooling in VLSI circuit.

Bier et al. [2] have manufactured a counter flow microchannel heat exchanger by precision cutting. That microchannel heat exchanger is tested with water as working fluid for convective heat transfer. A volumetric heat transfer coefficient of 0.324 MW/(m^{3}K) was obtained.

Friedrich et al. [3] have manufactured a trapezoidal shaped microchannel heat exchanger by diamond machining. In that heat exchangers counter flow arrangement is provided. They tested with water as working fluid and a volumetric heat transfer coefficient of nearly 0.45 MW/(m^{3}K).

Ravigururajan et al. [4] have investigated on single-phase parallel flow rectangular cross-sectional microchannel heat exchanger. They used Refrigerant-124 as a working fluid. They observed that the increase in heat transfer coefficient may be attributed for the thickening of the boundary layer in a narrow channel.

Wei [5] fabricated a stacked rectangular microchannel heat sink using micro fabrication techniques. Experiments were conducted for the study of thermal performance of the stacked microchannel structure by making the overall thermal resistance was less than 0.1 K/W for both counter-flow and parallel-flow configurations. For low volumetric flow rates, the parallel-flow arrangement shows a lower overall thermal resistance when compared with that of the counter-flow arrangement, however, at high volumetric flow rates for counter-flow as well as for parallel flow arrangements; the overall thermal resistances are indistinguishable. The volumetric flow rate ratio between the top and bottom layers could be obtained to achieve high thermal efficiency.

Hasan et al. [6] evaluated the effect of size and cross-section of microchannels for a counter-flow arrangement in a heat exchanger by using numerical simulation. The effect of cross-section of the channels were studied for different channel shapes such as square, circular, rectangular, iso-triangular, and trapezoidal shapes. Out of all the channels circular microchannels gave the best overall performance. Then square microchannel gave the second best overall performance. By increasing the total number of channels in a microchannel heat exchanger, the heat transfer simulation is enhanced with the increase in pressure drop.

Dang et al. [7] have demonstrated a study on the simulation of a trapezoidal shaped micro heat exchanger by parallel flow arrangement. Using the geometrical dimensions and the flow conditions associated with this micro heat exchanger, a total heat flux of 13.6 W/cm^2 was achieved by numerical method. Besides, for this microchannel heat exchanger, the heat transfer and fluid flow behaviors in terms of the temperature profile, velocity field, and Reynolds number distribution were determined.

For the present study, a single-phase heat transfer phenomenon is obtained from numerical simulation of triangular, rectangular, pentagonal and circular cross-sectioned stacked microchannels heat sinks.

The two cases which were considered for this analysis are:

(1) The counter-flow arrangement
(2) The parallel-flow arrangement.

2. ANALYSIS

The analysis has been carried out on the stacked microchannel heat sink with various cross-sections by using "Solid Works Flow Simulation" software.

2.1. *Computational Domain:*

Fig-2.1 shows rectangular microchannel heat sink with different dimensional parameters,

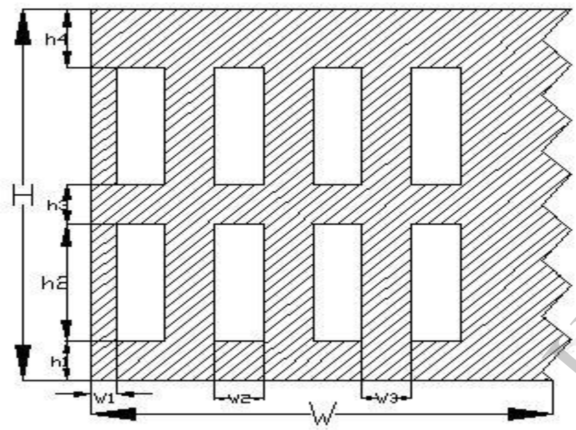

Figure -2.1: sectional view of rectangular stacked microchannel

The dimensions of other cross-sections are mentioned as follows,

Table -1: various dimensions used in different microchannels

Section Cross-section	**h_1 (μm)**	**h_2 (μm)**	**h_3 (μm)**	**h_4 (μm)**	**w_1 (μm)**	**w_2 (μm)**	**w_3 (μm)**
Rectangular	0.18	0.18	0.14	0.2	0.02	0.06	0.02
Triangular	0.18	0.07	0.11	0.28	0.02	0.06	0.02
Pentagonal	0.18	0.12	0.10	0.30	0.02	0.05	0.02
Circular	0.21	0.05	0.16	0.33	0.02	0.05	0.02

Total width of heat sink W = 0.82 μm

Total height of heat sink H = 0.7 μm

Total length of heat sink L = 2 μm

The following assumptions have been made for the analysis:

i. The heat transfer by forced convection is in steady state,
ii. the fluid flowing through the microchannels is incompressible,
iii. Viscosity of fluid is negligible,
iv. The fluid flow is transitional.

2.2. *Governing equations:*

The governing equations for the flow field, continuity equation, momentum equations in three directions (x, y, and z), and energy equation are as follow:

Continuity equation: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$

Momentum equation: $\frac{\partial P}{\partial x} = \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$

$$\frac{\partial P}{\partial y} = \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)$$

$$\frac{\partial P}{\partial z} = \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{k_l}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

Where u, v and *w* are velocities along *x*, y and *z* directions. T denotes temperature, k_l, c_P, and r are thermal conductivity, specific heat, and density of liquid, respectively.

2.3 *Boundary conditions:*

Since the governing equations are being solved by partial differential equations their solution is affected by boundary conditions. The following boundary conditions are applied to the computational domain in the present study.

- A mass flow rate of 0.00001 kg/s is taken along the microchannels.
- Pressure at the exit of the channel is static pressure.
- A uniform heat flux of 750 x 10^6 W/m^2.

2.4 Desired outputs:

Following are the desired outputs from the flow simulation process,

- Surface temperature of channel,
- Max. temperature of liquid,
- Static pressure,
- Volumetric heat transfer coefficient,
- Velocity of flow.

2.5 Flow simulation:

Once the computational domain is constructed with the help of required dimensions, by defining the boundary conditions and goals the simulation process is applied in order to obtain required results.

3. RESULTS AND DISCUSIONS

3.1 Flow Trajectories:

The performance of various cross-sections of microchannel heat sinks like rectangular, triangular, pentagonal and circular channels is evaluated. The results are compared for parallel and counter flow arrangement of each followed by comparison among each configuration. The following figures shows the pressure and temperature trajectories of different configuration microchannels.

Fig 3.1 represents the pressure trajectories of parallel flow rectangular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 101396.7 Pa from inlet to exit of the channel.

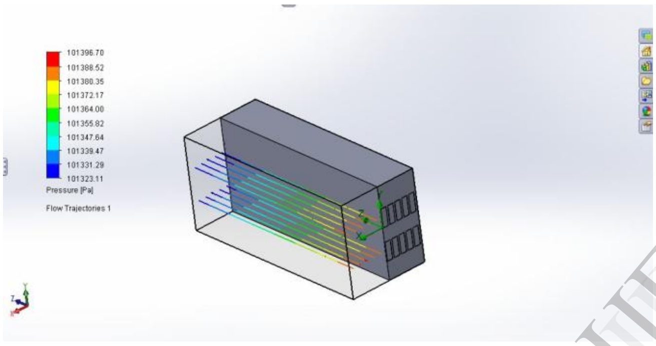

Fig-3.1: Pressure Trajectories of parallel flow rectangular microchannel

Fig 3.2 represents the temperature trajectories of parallel flow rectangular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 318.6^0C from the inlet to exit of the channel.

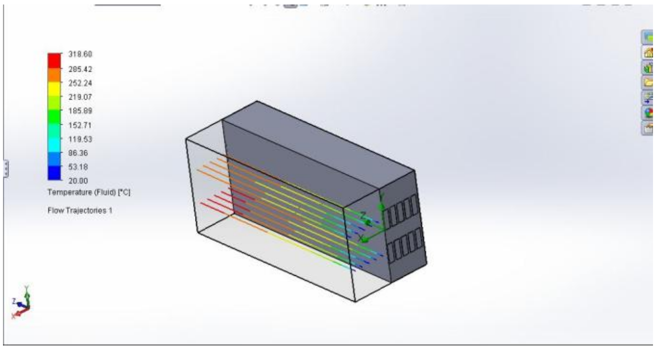

Fig-3.2: Temperature Trajectories of parallel flow rectangular microchannel

Fig 3.3 represents the pressure trajectories of counter flow rectangular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 101391.6 Pa from inlet to exit of the channel.

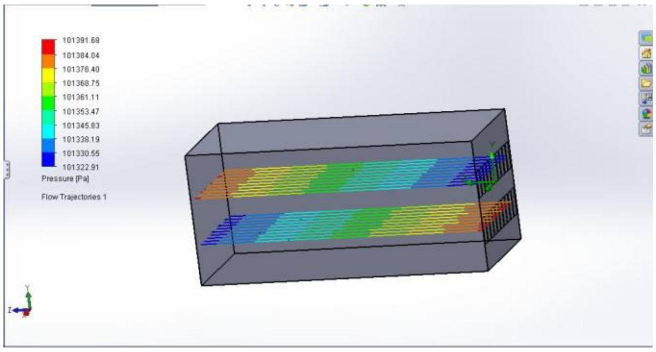

Fig-3.3: Pressure Trajectories of counter flow rectangular microchannel

Fig 3.4 represents the temperature trajectories of counter flow rectangular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 333.61^0C from the inlet to exit of the channel.

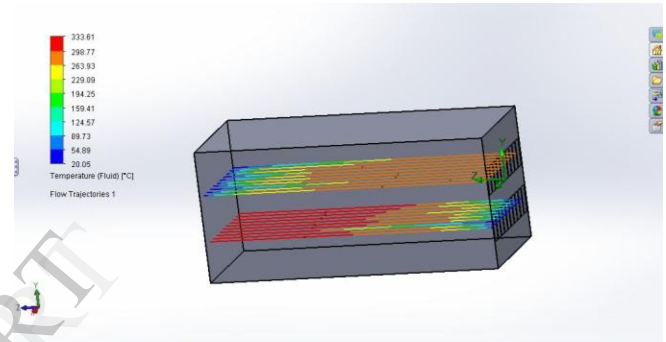

Fig-3.4: Temperature Trajectories of counter flow rectangular microchannel

Fig 3.5 represents the pressure trajectories of parallel flow triangular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 102244.4 Pa from inlet to exit of the channel.

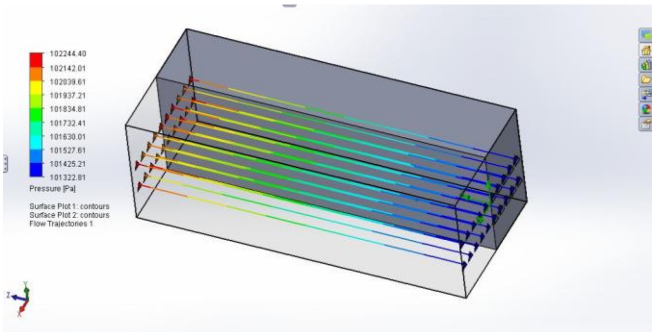

Fig-3.5: Pressure Trajectories of parallel flow triangular microchannel

Fig 3.6 represents the temperature trajectories of parallel flow triangular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 306.24^0C from the inlet to exit of the channel

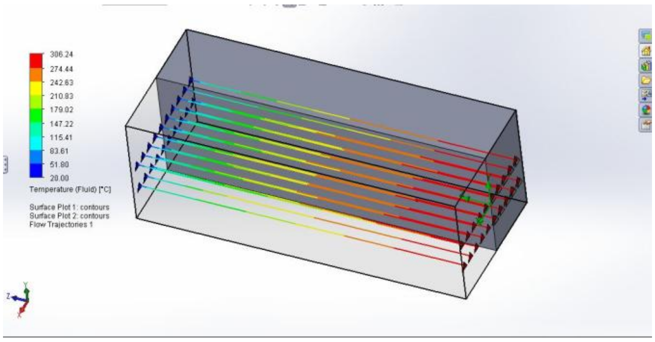

Fig-3.6: Temperature Trajectories of parallel flow triangular microchannel

Fig 3.7 represents the pressure trajectories of counter flow triangular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 102202.6 Pa from inlet to exit of the channel.

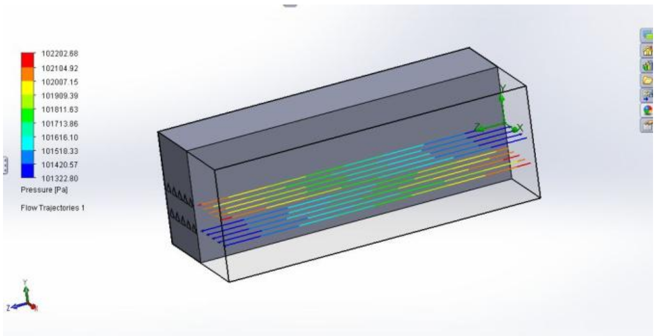

Fig-3.7: Pressure Trajectories of counter flow triangular microchannel

Fig 3.8 represents the temperature trajectories of counter flow triangular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 321.94^0C from the inlet to exit of the channel.

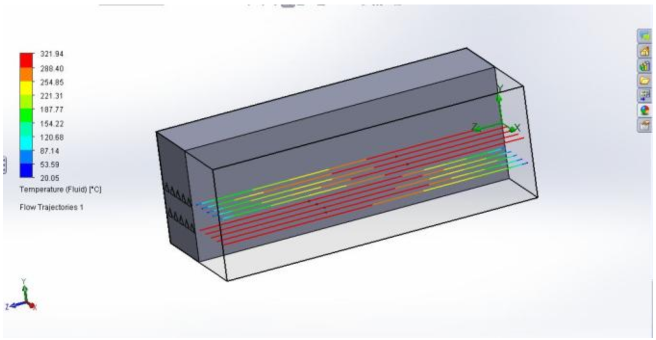

Fig-3.8: Temperature Trajectories of counter flow triangular microchannel

Fig 3.9 represents the pressure trajectories of parallel flow pentagonal stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 102004.35 Pa from inlet to exit of the channel.

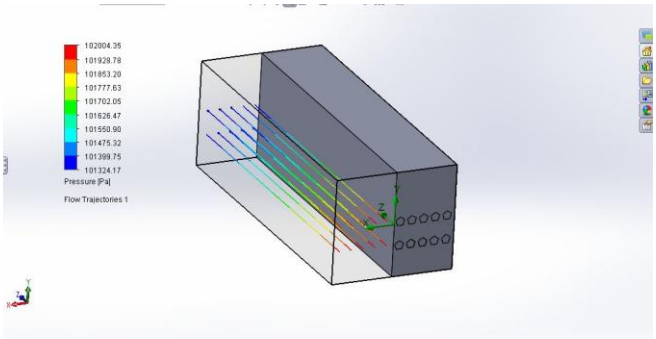

Fig-3.9: Pressure Trajectories of parallel flow pentagonal microchannel

Fig 3.10 represents the temperature trajectories of parallel flow pentagonal stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 309.57^0C from the inlet to exit of the channel.

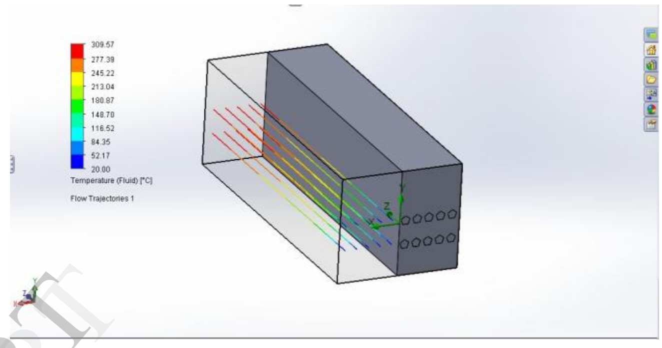

Fig-3.10: Temperature Trajectories of parallel flow pentagonal microchannel

Fig 3.11 represents the pressure trajectories of counter flow pentagonal stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 101990.18 Pa from inlet to exit of the channel.

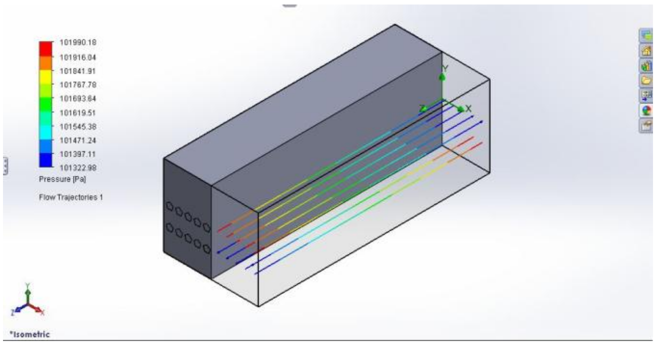

Fig-3.11: Pressure Trajectories of counter flow pentagonal microchannel

Fig 3.12 represents the temperature trajectories of counter flow pentagonal stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 319.88^0C from the inlet to exit of the channel.

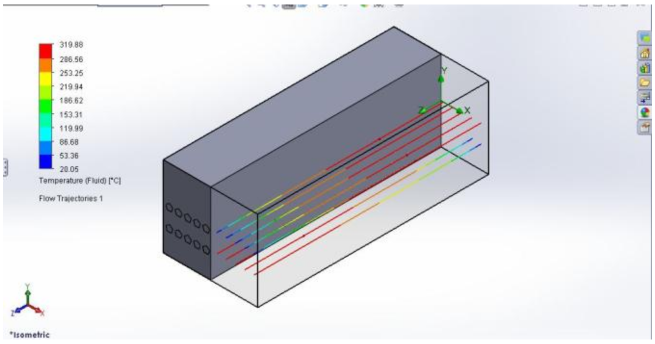

Fig-3.12: Temperature Trajectories of counter flow pentagonal microchannel

Fig 3.13 represents the pressure trajectories of parallel flow rectangular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 101829.057 Pa from inlet to exit of the channel.

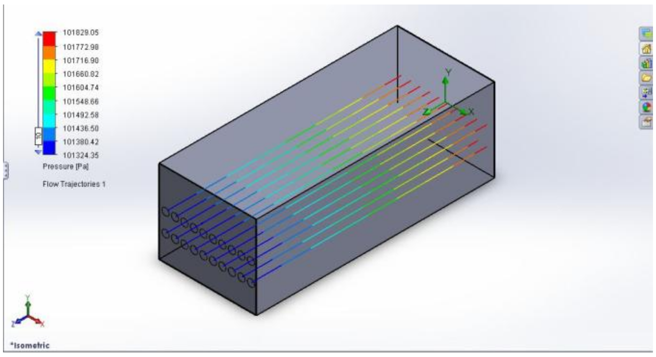

Fig-3.13: Pressure Trajectories of parallel flow circular microchannel

Fig 3.14 represents the temperature trajectories of parallel flow circular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 315.13^0C from the inlet to exit of the channel.

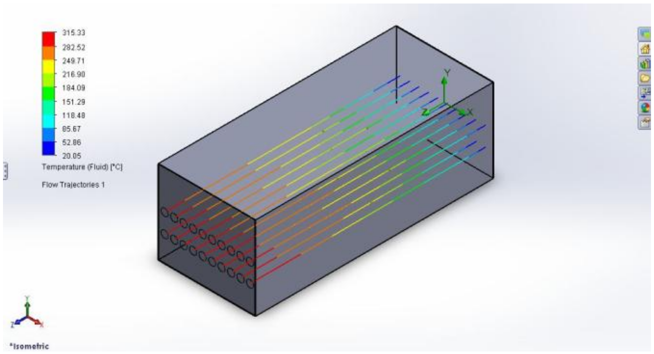

Fig-3.14: Temperature Trajectories of parallel flow circular microchannel

Fig 3.15 represents the pressure trajectories of counter flow circular stacked microchannel heat sink where the pressure varied from 101323.11 Pa to 101829.66 Pa from inlet to exit of the channel.

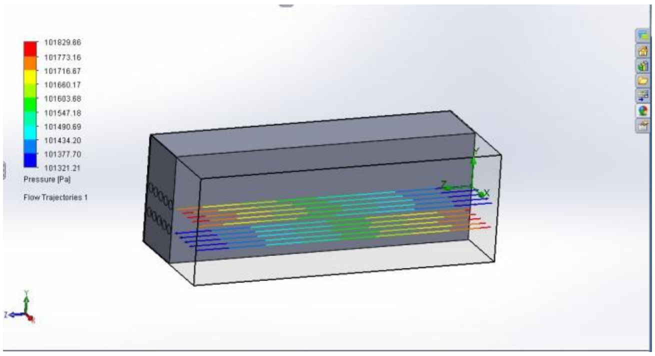

Fig-3.15: Pressure Trajectories of counter flow circular microchannel

Fig 3.16 represents the temperature trajectories of counter flow circular stacked microchannel heat sink where the temperature of fluid varied from 20^0C to 316.41^0C from the inlet to exit of the channel.

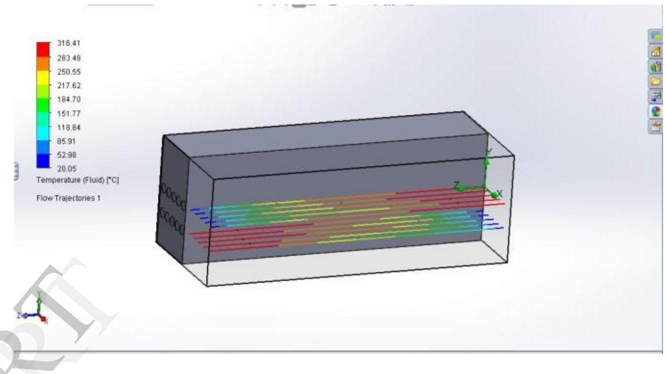

Fig-3.16: Temperature Trajectories of counter flow circular microchannel

Table 3.1 shows the results obtained from flow simulation of different cross-sectional microchannels like rise in the temperature of fluid, static pressure drop cross the microchannels and volumetric heat transfer coefficient from parallel and counter flow. From the results we can observe that, the temperature of fluid coming out from rectangular microchannel in both parallel (318.6^0C) and counter flows (33.61^0C) are more when compared to other cross-sectional microchannel heat sinks.

Table-3.1: Results obtained from simulation

S. No.	Microchannel Used	Quantity	Parallel Flow		Counter Flow	
			Min	Max	Min	Max
1	*Triangular*	Temperature of fluid (°c)	20	306.24	20	321.94
		Static Pressure (Pa)	101324.69	102295.97	101322.80	102202.68
		Volumetric heat transfer coefficient (W/cm^3.^{0}c)	0.477		0.503	
2	*Rectangular*	Temperature of fluid (°c)	20	318.6	20	333.61
		Static Pressure (Pa)	101323.18	101397.95	101322.91	101391.68
		Volumetric heat transfer coefficient (W/cm^3.^{0}c)	0.599		0.64	
3	*Pentagonal*	Temperature of fluid (°c)	20	309.57	20	319.88
		Static Pressure (Pa)	101324.17	102004.35	101322.98	101990.18
		Volumetric heat transfer coefficient (W/cm^3.^{0}c)	0.378		0.387	
4	*Circular*	Temperature of fluid (°c)	20	315.33	20	316.41
		Static Pressure (Pa)	101324.35	101829.05	101321.21	101829.66
		Volumetric heat transfer coefficient (W/cm^3.^{0}c)	0.217		0.215	

3.3 Validation of CFD:

The heat transfer and fluid flow models used in the present study have been developed and simulated using “SOLID WORKS FLOW SIMULATIOM” process. However to validate the results we calculate the thermal resistances and are compared against experimental results.

Calculated results are agreeing with the experimental values by using “Multi-objective optimization” as validation technique.

4. CONCLUSION

The fluid flow and heat transfer processes in a rectangular, triangular, pentagonal and circular micro-channel heat sink with parallel and counter flow were analyzed numerically temperature rise in fluid, pressure drop across microchannels and volumetric heat transfer coefficients were obtained. Furthermore, the validation of results by using multi-objective optimization method was investigated based on the numerical results.

From the numerical study on different micro-channel heat sinks (rectangular, triangular, pentagonal and circular) by parallel and counter flow study we conclude that rectangular microchannel heat sink will give better volumetric heat transfer coefficient 0.64 W/cm^{3}K in counter flow when compared to other cross-sectional microchannel heat sinks.

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