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Avinash Kumar R.
PSG Institute of Technology and Applied Research

M. Kavitha
PSG College of Technology

Sriman Adhithya Srinivasan
PSG Institute of Technology and Applied Research

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R. Avinash Kumar, M. Kavitha, P. Manoj Kumar, and S. Sriman Adhithya

Effect of Channel Shapes on Fluid Flow and Heat Transfer in Microchannel - A Numerical Study

R Avinash Kumar[1, a)], M Kavitha[2], P Manoj Kumar[1] and S Sriman Adhithya[3]

[1, a & 1]Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Tamilnadu, India.
[2]Department of Metallurgical Engineering, PSG College of Technology, Tamilnadu, India.
[3]Titan Engineering & Automation Solutions, Tamilnadu, India.

[a)]Corresponding author: avinash@psgitech.ac.in

Abstract. Increase in applications of micro devices in MEMS and NEMS, demands efficient cooling systems. Due to miniaturization, the conventional cooling systems fail to satisfy the required cooling performance. Therefore design and analyses of optimized cooling system for different micro devices are required for its better performance. The present work investigates the conjugate heat transfer analysis in selected configurations of microchannels (rectangular, circular and trapezoidal with two configurations) with water as coolant. Three dimensional numerical simulations were performed using commercially available package ANSYS FLUENT 18.1. This work proposes a way to analyse the conjugate heat transfer properties in different microchannels cross sections. The steady state three-dimensional numerical simulations were carried out for single phase forced convection laminar flow. The present analyses focus on comparative study of heat transfer characteristics in different shape of the channels. The dimensions of microchannels were chosen by considering hydraulic diameter as constant in different geometrical shapes. The inlet velocities were varied as 1m/s, 1.5m/s, 2m/s, 2.25m/s, 2.5m/s and parameters such as Nusselt number, pressure drop and outlet temperature at constant heat input were determined and compared. It is revealed that geometrical shapes of microchannels have significant effects in the heat transfer characteristics.

INTRODUCTION

In the last two decades, the flow in microchannels has been widely investigated for efficient and faster cooling of electronic devices. The reduction in size and their high heat transfer characteristics makes microchannels efficient heat exchangers. In addition to this, its lightweight, small size, and minimum material usage add significant contribution for its effective usage. The more compact heat exchangers with reduced diameters of microchannels result in higher heat transfer coefficients through additional surface area per unit volume. The main challenges in fluid flow through microchannels are the difficulties in fabrication, filtering of the operating fluid, high pressure drop and therefore the increase in pumping power needed.

Muhammad Mustafizur Rahman, [1] developed experimental measurements for heat transfer coefficient and pressure drop in microchannel heat sinks. Performance test on two different channel patterns namely, series pattern and parallel pattern were conducted. Tests were conducted with water as the working fluid. The measured values were used to calculate coefficient of friction, average and local Nusselt number. Dorin Lelea et al., [2] carried experimental and numerical research works on heat transfer of microchannels made of stainless steels. The experimental setup was designed with distilled water as working fluid to investigate the average friction factor and heat transfer characteristics. Dorin Lelea [3] selected straight circular microchannels for geometric optimization, considering inner diameter of 900μm with a fixed pumping power basis where thermal and hydrodynamic results were compared.

Mohammed et al., [4] conducted numerical analyses of wavy micro channel heat sink (WMCHS) with rectangular cross-section and varying amplitudes for investigating the heat transfer and fluid flow characteristics.

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The studies indicated that, for constant Reynolds number and channel width, the pressure drop is inversely proportional to the channel depth. Sehgal et al., [5] conducted studies on flow arrangements of microchannel heat sinks to investigate the effect of entry and exit conditions. For the analyses, three flow arrangements named U-type, S-type, and P-type were considered. With least pressure drop and utmost heat transfer, the best performance was observed in U-type compared to other two configurations for a constant Reynolds number. Sui et al., [6] carried out direct numerical simulation to analyse the heat transfer in a periodic wavy channels with fully developed condition for rectangular cross sections. The results indicated enhanced heat transfer performance compared to straight channels of same cross sections due to the efficient mixing in wavy channels with penalty of pressure drop.

Anbumeenakshi and Thansekhar [7] carried out experimental investigation for Reynolds number range of 200–650 to analyze the flow maldistribution in twenty-five rectangular microchannel heat sinks made of aluminum with a diameter of 763µm using deionized water as the coolant. The studies were carried out for inlet configurations with vertical flow inlet rectangular, trapezoidal and triangular shaped headers. Less misdistribution was observed in vertical flow inlet configurations. Trapezoidal and triangular headers offered less flow maldistribution at low flow rates while rectangular was best suited for higher flow rates. Khorasanizadeh and Sepehrnia [8] investigated laminar flow of water in four different configurations of trapezoidal microchannel heat sinks, in which the temperature dependent properties improved heat transfer rate and decreased thermal resistance.

Raghuraman et al., [9] conducted numerical studies on rectangular microchannel for different aspect ratio to obtain the efficient heat removal. Aspect ratios of 20, 30 and 46 were considered for Reynolds number ranging from 50 to 350. Considering all performance parameters, aspect ratio 30 was preferred for efficient heat removal compared to other two ratios. At constant flow rate of water and with secondary flow channel, Shi et al., [10] obtained a significant reduction for thermal resistance and pumping power compared to conventional smooth channel. Considering semi-circular type of grooves inside the channel, Pankaj [11] carried out three-dimensional simulations in a trapezoidal microchannel for constant heat flux and different pressure drop conditions. The results showed 12% increase in heat transfer performance compared to the rectangular microchannel. Sanjeev et al., [12] conducted experimental and numerical studies for air cooling with straight, wavy and branched wavy channels. Studies indicated an enhanced thermal-hydraulic performance for branched wavy heat sink.

Deng et al., [13] conducted studies on periodic expanded-constrained microchannels (PECM) heat sinks. The cooling efficiency PECM was compared with rectangular microchannels. In the test range considered, PECM showed a tremendous enhancement of heat transfer compared to the rectangular one. 50% to 117% enhancement of heat transfer was observed in this case. The effect of manufacturing techniques on the performance of microchannels were analysed by Diao and Zhao [14]. Sintered Cu and Porous Cu microchannels manufactured by Lost Carbonate Sintering (LCS) were compared with conventional machined microchannels. The studies indicated that the conventional machined microchannel offered less pressure drop compared to sintered Cu and LCS Cu samples. Both sintered and LCS samples showed better heat transfer performance in comparison with conventional machined channels.

Based on the previous literatures, it was observed that the main challenges in fluid flow through channels are the difficulties in fabrication, and filtering of the operating fluid, high pressure drop and therefore the increase in pumping power needed. The present work demonstrates the analyses of different geometrical configurations of microchannels to compare the pressure drop and maximum heat transfer keeping the hydraulic diameter of the channels constant for various Reynolds Numbers. In the analyses, thermal analyses of channels used in general has been analyzed and compared for Reynolds Numbers ranging from 100 to 500.

MICROCHANNEL CONFIGURATIONS AND NUMERICAL SIMULATION

A rectangular, circular and trapezoidal configuration was modeled for the numerical simulation for a hydraulic diameter of 152 µm as shown in Figure 1. Water is selected as working fluid in the microchannel and a fixed heat input was supplied at the bottom plate of the heat sink for all the configurations. Copper is chosen as channel material. The dimensions of the microchannels of each cross section are tabulated in Table 1 to 3. The length of the channel has been fixed as 10000µm for all the cross sections. To simplify the computations, the assumptions were made based on the understanding of the flow features acquired through the literature survey.

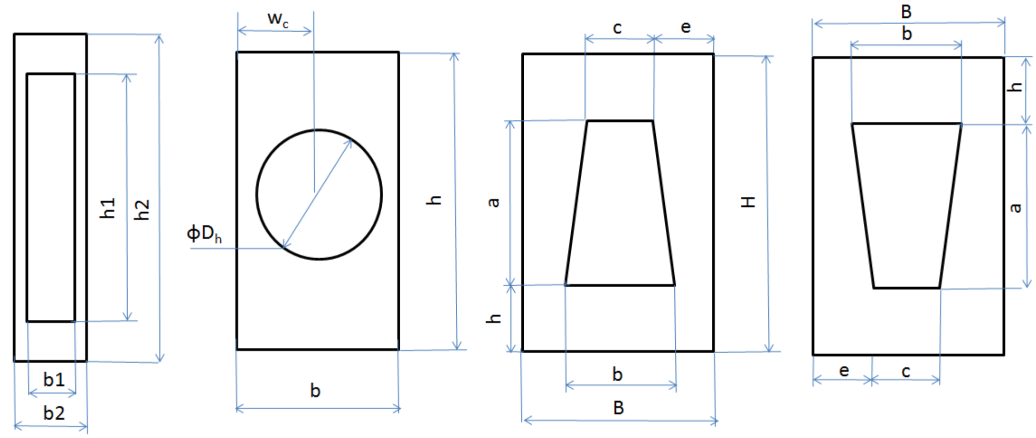


FIGURE 1. Microchannel configurations (Rectangular, Circular and Trapezoidal configuration 1&2)

TABLE 1. Geometrical data of rectangular configuration

b1(μm)	b2(μm)	h1(μm)	h2(μm)	L(mm)
85	141	700	900	10

TABLE 2. Geometrical data of circular configuration

b (μm)	h(μm)	W_c(μm)	D_h (μm)	L(mm)
207	351	103.7	151	10

TABLE 3. Geometrical data of Trapezoidal configuration 1&2 configuration

a(μm)	b(μm)	c(μm)	e(μm)	h(μm)	H(μm)	B(μm)	L(mm)
246	135	85	125	100	495.54	335	10

COMPUTATIONAL MODELING

The commercial CFD package ANSYS FLUENT 18.1 was used to conduct the 3D conjugate heat transfer analyses. In order to consider the effects of both conduction and convection, a conjugate heat transfer simulation was chosen for the analyses. The equations that govern the heat transfer analyses are expressed as follows:

Continuity equation $$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4.1)$$

X- Momentum equation $$\rho_f\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu_f\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (4.2)$$

Y-Momentum equation $$\rho_f\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu_f\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (4.3)$$

Z- Momentum equation $$\rho_f\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu_f\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (4.4)$$

Energy equation $$c_p\left(u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}+w\frac{\partial T_f}{\partial z}\right)=k_f\nabla^2 T_f \text{(for fluid)} \quad (4.5)$$

$$k_s\nabla^2 T_s=0 \quad \text{(for solid)} \quad (4.6)$$

The thermo physical properties of water for the computation are density, ρ_f is 1000g/cc, Specific heat, C_p is 4816J/kg K, Thermal conductivity, k_f is 0.5918W/mK, Viscosity, μ_f is0.00085288Ns/m2. Velocity inlet and pressure outlet boundaries are defined for the inlet and outlet of the channel. At the wall/fluid interface, no interfacial resistance and no-slip boundary conditions are assumed. The inlet temperature of water is 300K for the selected velocities of 1, 1.5, 2, 2.25, and 2.5 m/s(Re = 100 to 500). A constant heat input of 1410W was applied at the bottom plate of the channel and the pressure of the outlet is 0 Pa (gauge pressure). The pressure based solver is used for the current study. For pressure-velocity coupling, SIMPLE scheme has been selected due to the incorporation of collocated grid. The continuity, momentum and energy equations were discretized using second order upwind scheme and the 'Standard' scheme is used for pressure interpolation. The residual convergence limit is set as NONE for continuity, momentum equations and energy equation as shown in Figure. 2.

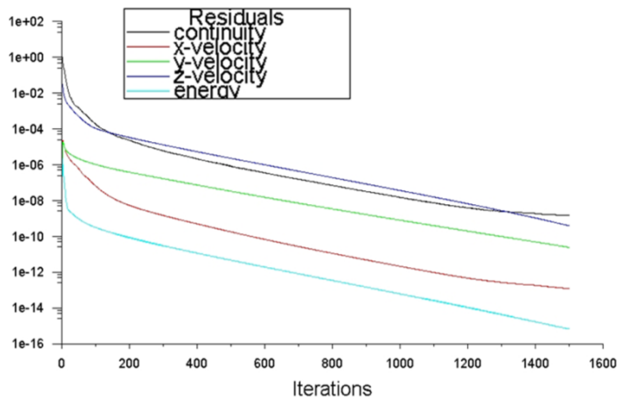
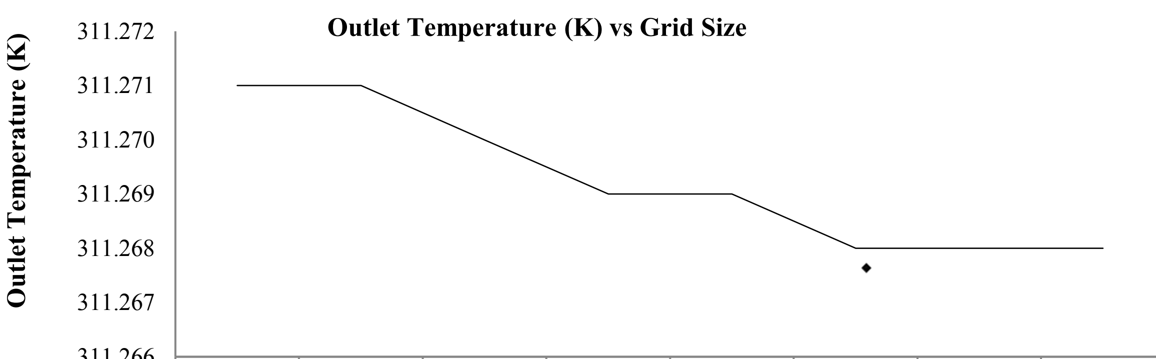


FIGURE 2. Convergence criterion for different geometries

GRID INDEPENDANCEY TEST

To assess the impact of grid size numbers, grid independence test has been conducted for the following grid size numbers mentioned in the Figure 3. Analyses are conducted by monitoring the outlet temperature of the channel for different grid size. From the grid independency test it is concluded to conduct the analysis of channels with a grid size of 180×50×40 (635129 nodes and 585900 elements)



	65*20*10	70*25*15	120*35*25	150*40*30	160*45*35	180*50*40	190*55*45	200*60*50
Temperature (K)	311.271	311.271	311.27	311.269	311.269	311.268	311.268	311.268

FIGURE 3. Grid independency test

RESULTS AND DISCUSSIONS

With water as working fluid, flow through channel was analysed using specified velocities and the parameters like channel outlet temperature, pressure drop, pumping power and heat transfer coefficient has been calculated and compared for the different channel configurations selected. The findings of the current studies are reported below.

Channel Outlet Temperature

Figure 4. shows the outlet temperature plotted against Reynolds number for different configuration of microchannels. The results show that the outlet temperature of circular configuration is higher compared to other configurations because of more heat transfer with reduced losses. Rectangular configuration has less outlet temperature compared to other configurations. The average outlet temperatures for the range of Reynolds number are 303.2 K, 319.2 K, 308 K and 307.5 K for rectangular, circular and trapezoidal configurations respectively. The distribution of temperature along the length of the channel is also plotted and it has been found that the circular channel shows better performance compared to other configurations as shown in Figure 5.

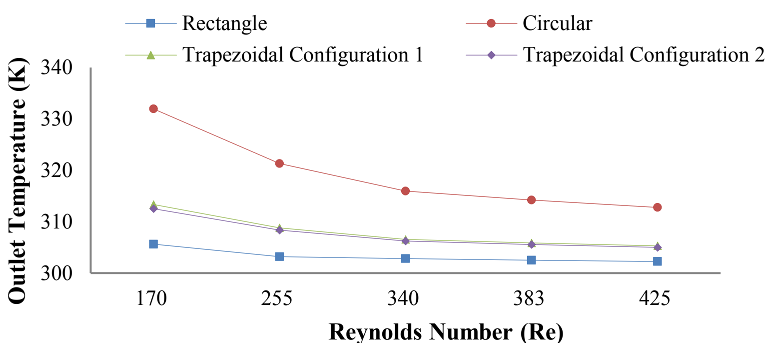


FIGURE 4. Dependence of outlet temperature on the Reynolds Number

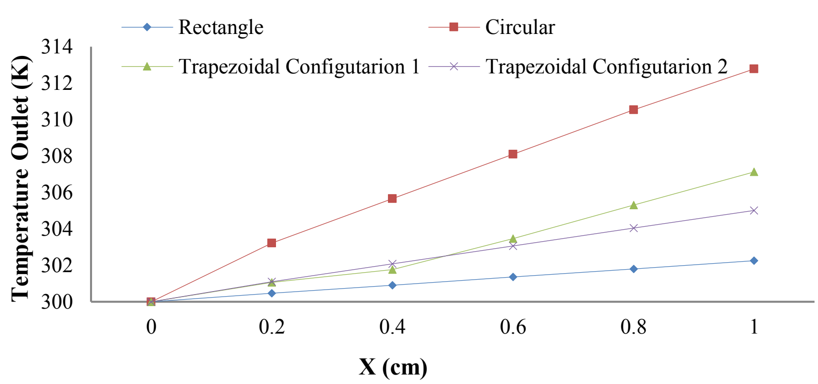


FIGURE 5. Distribution of temperature along the channel length

Channel Pressure Drop and Pumping Power

The pressure drop for the channel configurations has been determined and analyzed for the selected Reynolds number as shown in Figure 6. From this figure, it is evident that the pressure drop increases with increase in Reynolds number. The losses increase with fluid kinetic energy and these losses are mainly due to flow at the edges of the cross section. Since the flow restriction is less in circular configuration and more in rectangular configuration, the circular channel offers less pressure drop compared to other configurations. The values of pressure drop obtained are listed in Table 4. With the pressure drop obtained, the pumping power for the channel has been calculated using the relation, $W_p = \left(\frac{1}{\eta_p} \times \frac{\dot{m}}{\rho}\right) \Delta P$, wherepump efficiency is assumed as 70%. Figure 7.shows the pumping power requirements for the selected range of Reynolds Number and it has been found that the circular configurations have the minimal requirement.

Effect of Heat Transfer Coefficient

The heat transfer coefficient (h) for the microchannel configurations are calculated using the following formula, $h = \frac{\dot{m}C_p(T_{out}-T_{in})}{A(T_w-T_f)}$, where $\dot{m}$is mass flow rate of water (kg/s), C_p is specific heat of water (J/kg K), T_{in} is inlet temperature of water (K) is 300 K, Tout is outlet temperature of water (K), A is surface area of the geometry (m^2), T_w is wall temperature of the geometry (K), T_f is outlet fluid temperature (K). From Figure 8, it may infer that circular configuration has higher heat transfer coefficient and rectangular configurations shows the least. The heat transfer coefficient shows an increasing trend with increase in Reynolds number for all the configurations. The rectangular and trapezoidal configuration has sharp corners where the fluid will be stagnant and the heat transfer happens by conduction mode, whereas in the circular configuration the entire heat transfer is by convection mode.

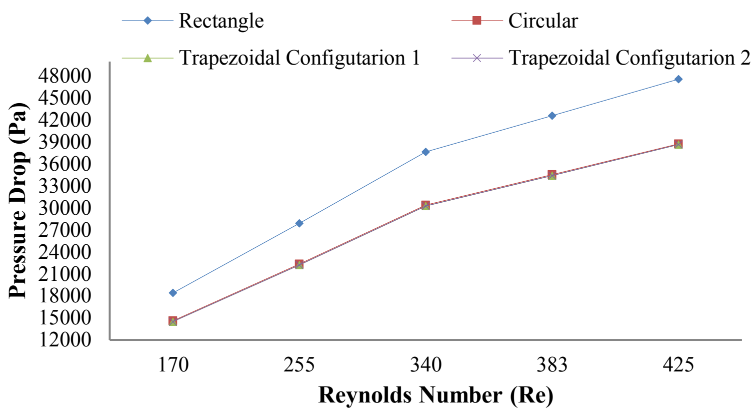


FIGURE 6. Dependence of pressure drop on the Reynolds Number

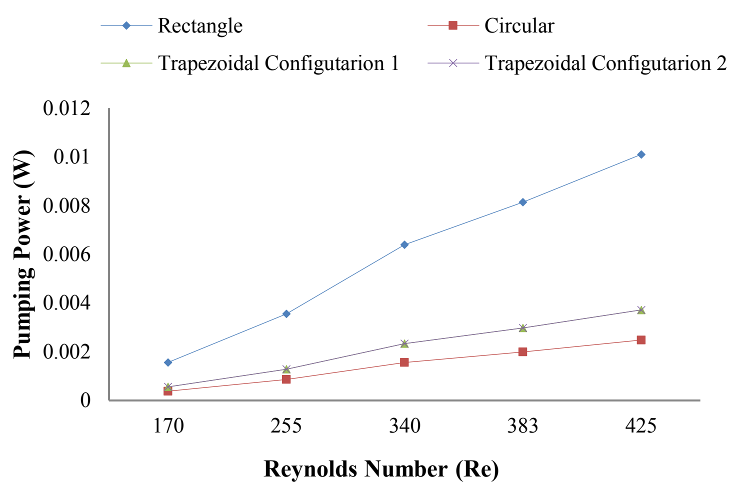


FIGURE 7. Dependence of pressure drop on the Reynolds Number

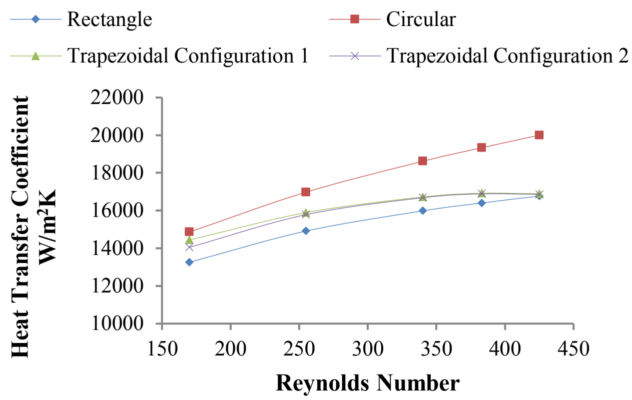


FIGURE 8. Dependence of heat transfer co-efficient on the Reynolds Number

TABLE 4. Pressure drop details of selected configurations

S.No	Microchannel Configuration	Reynolds Number	Pressure Drop (Pa)
1		170	18411.5
		255	27933.2
	Rectangle	340	37663.5
		383	42606.5
		425	47601.3
		170	14605.3
2		255	22358.2
		340	30411.4
	Circular	383	34550.7
		425	38765.2
		170	14497.9
3		255	22235.3
	Trapezoidal	340	30295.8
	Configuration 1	383	34446.5
		425	38676.9
4		170	14498.6
		255	22237
	Trapezoidal	340	30298.7
	Configuration 2	383	34450.1
		425	38681.3

CONCLUSIONS

The present study investigates the comparison of heat transfer characteristics of the selected channel configurations (rectangular, circular, trapezoidal configuration 1&2) at constant heat input for same hydraulic diameter at velocities 1 m/s, 1.5m/s, 2 m/s, 2.25 m/s, and 2.5 m/s. The following conclusions are obtained from the analysis,

In the analysis, circular configuration has better heat transfer characteristics compared to other geometries; this is due to more convective heat transfer in the solid- fluid interface. The improvement in average outlet temperature and heat transfer coefficient for the circular channel was 5.28 and 16.12% compared to rectangular one.

Rectangular configuration has less heat transfer characteristics, for the same hydraulic diameter because of less fluid flow area compared to other configurations.

For both configurations of trapezoidal, the heat transfer characteristics are more over the same. The trapezoidal configurations shows significant changes in heat transfer characteristics compared to the rectangular configuration.

Rectangular configuration shows higher pressure drop than other configurations. This is due to minor losses. The minor loss is mainly due to flow at the edges of the cross section, since the flow restriction is less in circular configuration and more in rectangular configuration.

Pumping power requirement of the rectangular configuration is 50% more at higher Reynolds Numbers compared to other configuration because of more pressure drop.

REFERENCES

1. M. M. Rahman, 'Measurements of heat transfer in microchannel heat sinks',International Communications in Heat and Mass Transfer (2000), Vol.27(4), pp.495-506.
2. D.Lelea, S. Nishio and K. Takano, 'The experimental research on microtube heat transfer and fluid flow of distilled water', International Journal of Heat and Mass Transfer (2004), Vol.47(12), pp.2817-2830.
3. DorinLelea, 'Effects of inlet geometry on heat transfer and fluid flow of tangential micro-heat sink', International Journal of Heat and Mass Transfer (2010), Vol. 53, pp. 3562-3569.
4. H. A. Mohammed, P. Gunnasegaran, and N. H. Shuaib, 'Numerical simulation of heat transfer enhancement in wavy microchannel heat sink', International Communications in Heat and Mass Transfer (2011), Vol.38(1), pp.63-68.
5. S. S. Sehgal, K. Murugesan and S. K. Mohapatra, 'Experimental Investigation of the Effect of Flow Arrangements on the Performance of a Micro-Channel Heat Sink, Experimental Heat Transfer (2011), Vol.24, pp.215-233.
6. Y. Sui, C. J. Teo, and P. S. Lee, 'Direct numerical simulation of fluid flow and heat transfer in periodic wavy channels with rectangular cross-sections', International Journal of Heat and Mass Transfer (2012), Vol.55(1), pp.73-88.
7. C. Anbumeenakshi and M. R. Thansekhar, 'Experimental investigation of header shape and inlet configuration on flow maldistribution in microchannel, Experimental Thermal and Fluid Science (2016), Vol.75, pp.156-161.
8. H. Khorasanizadeh and M. Sepehrnia, 'Performance Evaluation of a Trapezoidal Microchannel Heat Sink with Various Entry/Exit Configurations', Journal of Applied Fluid Mechanics (2017), Vol. 10, pp.1547-1559.
9. D.R.S. Raghuraman, R. ThundilKaruppa Raj, P.K. Nagarajan, B.V.A. Rao, 'Influence of aspect ratio on the thermal performance of rectangular shaped micro channel heat sink using CFD code', Alexandria Engineering Journal (2017), Vol. 56, pp. 43-54.
10. Xiaojun Shi, Shan Li, Yingjie Mu and Bangtao Yin, 'Geometry parameters optimization for a microchannel heat sink with secondary flow channel', International Communications in Heat and Mass Transfer (2019), Vol. 104, pp.89-100.
11. Pankaj Kumar, 'Numerical investigation of fluid flow and heat transfer in trapezoidal microchannel with groove structure', International Journal of Thermal Sciences (2019), Vol.136, pp.33–43.
12. Sanjeev Kumar, Mithun Sarkar, Pawan Kumar Singh and Poh Seng Lee, 'Study of thermal and hydraulic performance of air cooled minichannel heatsink with novel geometries, International Communications in Heat and Mass Transfer (2019), Vol. 103, pp. 31-42.
13. Daxiang Deng, Liang Chen, Xiaolong Chen and Guang Pi, 'Heat transfer and pressure drop of a periodic expanded-constrained microchannels heat sink', International Journal of Heat and Mass Transfer (2019), Vol. 140, pp. 678-690.
14. KaikanDiao and Yuyuan Zhao, 'Heat transfer performance of sintered Cu microchannels produced by a novel method', International Journal of Heat and Mass Transfer (2019), Vol. 139, pp. 537–547.