Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Entropy Generation Minimization In Sinusoidal Cavities-Ribs Microchannel Heat Sink Via Secondary Channel Geometry

Open Access

Wan Mohd. Arif Aziz Japar[1], Nor Azwadi Che Sidik[1,*], Yutaka Asako[2]

[1] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 26 May 2019
Received in revised form 29 June 2019
Accepted 27 July 2019
Available online 30 July 2019

ABSTRACT

Microchannel heat sink is an advance cooling device that can fulfil cooling demand for electronic devices which have high power density in its microchip. However, fast development in electronic industry increases the power density rapidly. As consequence, the conventional design of microchannel heat sink such as Straight channel design (CR MCHS) inadequate to remove the heat flux generated by the electronic device due to thermal resistance and pumping power issue. Thus, in this paper, a novel design is proposed based on theory of entropy generation in laminar forced convection. Entropy generation due to fluid friction and heat transfer in Sinusoidal-cavities-ribs-secondary-channel microchannel heat sink (SD-RR-SC MCHS) was investigated numerically for the Reynold number of 100 – 800 at the constant wall heat flux of 100 W/cm2. Comparative study between proposed design (SD-RR-SC) with related microchannel heat sinks, namely, Rectangular ribs microchannel heat sink (RR MCSH), Sinusoidal cavities microchannel heat sink (SD MCHS) and Sinusoidal-cavities-ribs microchannel heat sink (SD-RR MCHS) was conducted in order to investigate the effect of cavities, ribs and secondary channel geometry on entropy generation augmentation. The result showed that all enhanced microchannel heat sinks obtained augmentation entropy generation number, $N_{s,a}$ less than 1 for all Re number. Among the enhanced microchannel heat sinks, SD-RR-SC MCHS achieved the lowest $N_{s,a}$ (0.43) at Re number of 500. Means that, the proposed design (SD-RR-SC MCHS) was less irreversibility compared to the other enhanced microchannel heat sink which contributed to the enhancement of heat transfer performance due to improvement of thermodynamic efficiency.

Keywords:
Cavities; ribs; secondary channel; laminar force convection; entropy generation; thermodynamic efficiency

1. Introduction

Over the past decade, the investigation of fluid flow and heat transfer characteristic induced by natural convection on thermal performance becomes a most interesting topic in a cooling system. The effectiveness of the cooling system in such application is very important to keep the temperature of a structure or electronic device from exceeding limits imposed by needs of safety and efficiency. The applications of the cooling system in thermal engineering are known for years and have been

* *Corresponding author.*
E-mail address: azwadi@utm.my (Nor Azwadi Che Sidik)

studied critically in theoretical as well practical point of view in various engineering applications such as building energy system, electronic device, chemical vapor deposition instruments, solar energy collector, furnace engineering and many more [1]. In recent years, rapid growth in the electronic industry has witnessed a new generation high performing dense chip packages in many modern electronic devices. The chip packages that work at high frequency has produced very high heat flux on the electronic devices. If it happens continually, the heat flux will create the hot spot on the electronic device and thus reduces the lifespan of the electronic devices due to the acceleration of the Mean Time to Failure (MTTF) as described by Black's equation [2]. The increase in power density and miniaturization of electronic packages has driven the direction of cooling system technology from air-cooling technology to advanced heat transfer technology due to the conventional method inadequate to remove very high heat flux [3]. However, the development of more compact electronic devices that will operate at high power density causes the thermal management of electronic devices becomes a very critical issue in the electronics industry due to lack of efficient technique to remove heat from the devices [4, 5].

During the past 30 years, many methods have been proposed in open literature in order to improve overall performance of microchannel heatsink with minimal thermal resistance and pressure drop that can satisfy the cooling demand. Generally, the methods can be categorized into two groups, active method and passive method. Active method will use external energy in its system while passive method no need for that. The passive method can be obtained by changing the channel design [6, 7], changing the fluid transport properties [8, 9] or both of them [10, 11]. Most of researcher has widely used the passive method due to its low cost and absence of moving part compared to active method [12]. Flow disruption technique is the one of the passive method that widely used in innovation of microchannel design due to its capability to increase the flow mixing and thus contributes to the heat transfer enhancement. Hong and Cheng [13] has investigated the effect of offset strip-fin on flow and heat transfer characteristic. It is found that, the fins have increased the flow mixing between the cold and hot coolant and thus enhanced the heat transfer performance. Other method to increase the degree of flow mixing is secondary flow method. In 2012, Lee *et al.,* [14] has designed oblique fins in copper microchannel heatsink for generating secondary flow that give a great impact on heat transfer performance that overcome pressure drop penalty issue. After two years, he and his research team [15] continued their investigation about oblique fin parameter in silicon microchannel heatsink. They have revealed that smaller oblique angle and smaller fin pitch will contributes to the heat transfer augmentation.

All of the studies reviewed here has demonstrated the heat transfer performance could be enhanced by using individual technique of passive method. However, pressure drop issue become the main constrain in the design development of microchannel heatsink. Nowadays, many researchers have used multiple technique of passive method in single phase flow for enhancement of microchannel performance. In 2013, Gong *et al.,* [16] has analysed the performance of microchannel structured by dimple and wavy shape. In their design, the effect of dimple number in wavy wall has been study numerically. They revealed that the presence of the dimple structure in wavy channel could enhanced the heat transfer performance and not apparently increase the flow resistance. Li *et al.,* [17] and Beng *et al.,* [18] have presented a numerical study to investigate the effect of ribs and cavities on fluid flow and heat transfer characteristic. The analysis revealed that combined effect of interruption, redevelopment of thermal boundary layer, the intensified mainstream disturbance and the chaotic mixing between hot and cold water has contributed to enhancement of heat transfer performance. In 2018, new features geometry such as secondary channel was proposed by Japar *et. al.,* [19] in TC-RR MCHS which designed by Li *et al.,* [17] in order to eliminate the vortices dead zone at the triangular cavities corner of the TC-RR MCHS.

Most of hybrid designs presented in open literature shows the optimum overall performance of MCHS is obtained at high Re number which consume to high pumping power. However, there has no researcher that study about the optimum overall performance enhancement at low Re number which contributes to reduction of pumping power consumption. In present study, we extend our previous work [20] by investigating the effect of cavities, ribs and secondary channel geometry on entropy generation in microchannel heat sink. The previous work showed that overall performance of the proposed design (SD-RR-SC MCHS) was obtained at low Re number (100≤Re≤450) without considering entropy generation augmentation. In this study, the analysis is extended by analysing the fluid flow and heat transfer irreversibility (entropy generation) in the proposed design. This analysis is very important because it will affect the thermodynamic efficiency and heat transfer process.

2. Geometry Parameter of Microchannel Heat Sink

All design of microchannel heat sinks in this paper are made by copper and each design consist of ten microchannels. Overall total length, Lt, total height, Ht and total width of the microchannel heat sinks are 10 mm, 0.4 mm and 3.15 mm respectively. However, in order to save the computational cost, only one symmetrical part of the microchannel heat sink for each design is adopted in present simulation as shown in Figure 1(a), 2(a), 3(a), 4(a) and 5(a). Table 1 shows parameter valued for all geometries that illustrated in Figure 1(b), 2(b), 3(b), 4(b) and 5(b). In order to study the effectiveness of secondary flow on hybrid microchannel heat sink performance, design development is started from reference design (CR MCHS) to single passive technique design (RR MCHS and SD MCHS). Next, hybrid design (SD-RR and SD-RR-SC) is developed based on the strength and weakness that found in single passive technique designs.

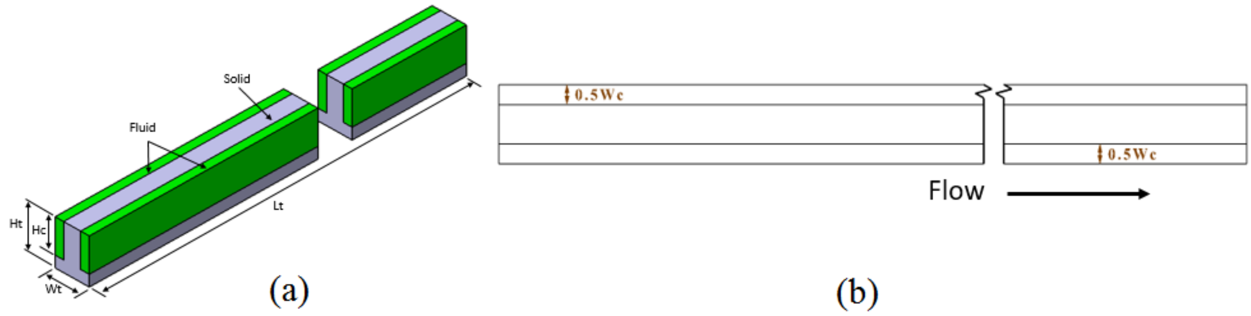

Fig. 1. CR MCHS (a) One symmetrical part (b) Geometry parameter

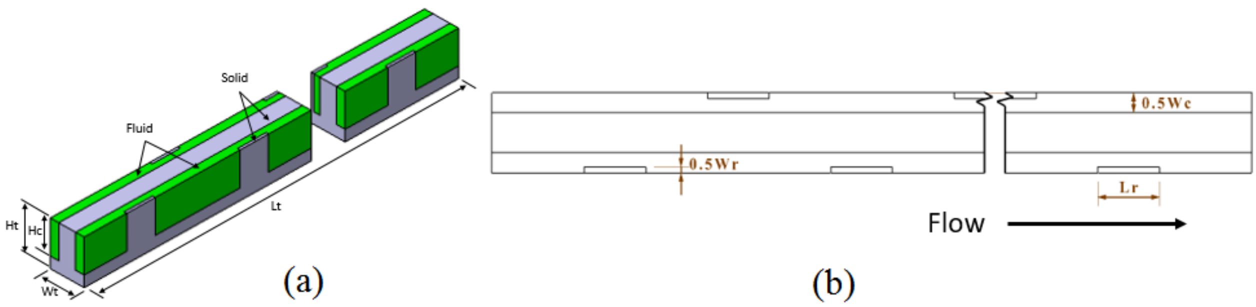

Fig. 2. RR MCHS (a) One symmetrical part (b) Geometry parameter

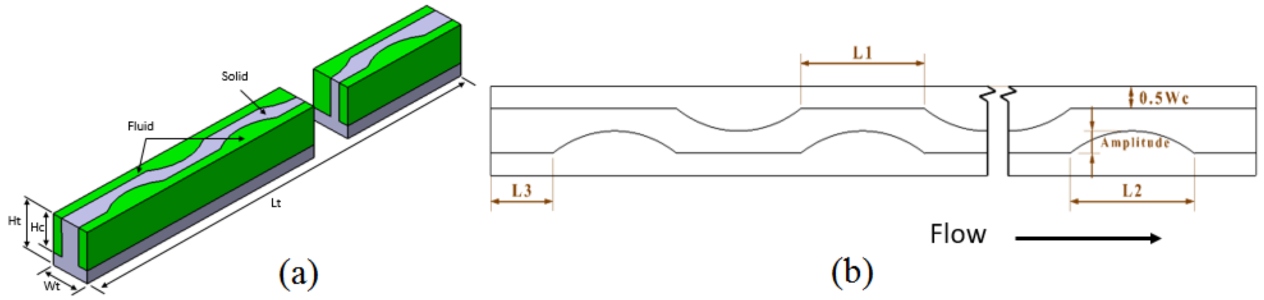

Fig. 3. SD MCHS (a) One symmetrical part (b) Geometry parameter

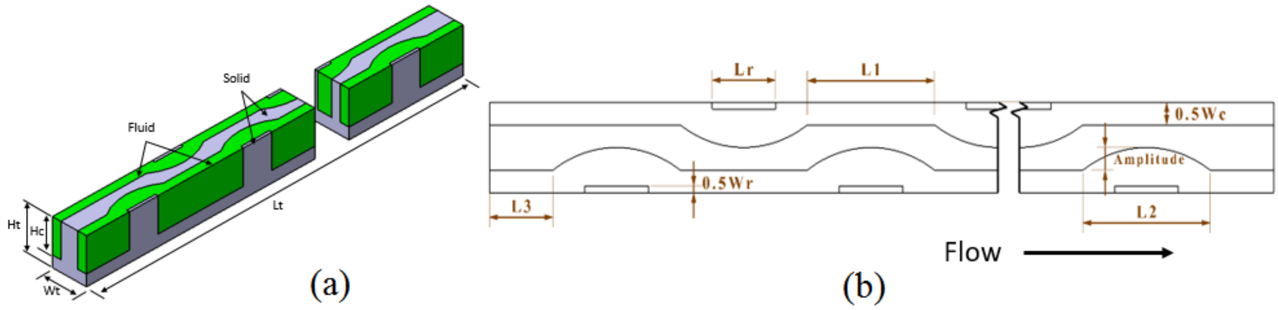

Fig. 4. SD-RR MCHS (a) One symmetrical part (b) Geometry parameter

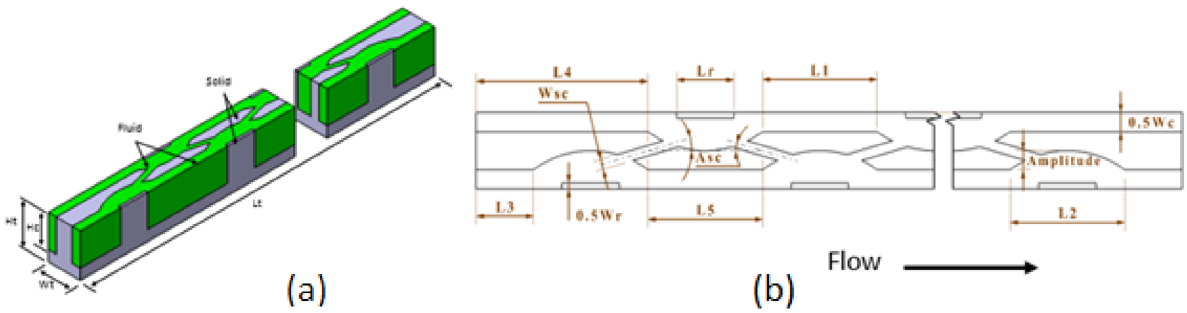

Fig. 5. SD-RR-SC MCHS (a) One symmetrical part (b) Geometry parameter

Table 1
Geometry parameters of SD-RR-SC MCHS

Lt (μm)	Wt & Hc (μm)	Ht (μm)	Wc (μm)	Lr & L3 (μm)	Wr (μm)	L1, L2 & L5 (μm)	L4 (μm)	Wsc (μm)	Asc (°)	Asd (μm)
10000	300	400	150	250	45	500	750	40	15	75

3. Numerical Method Approach

In order to analyse the performance of proposed geometry design (SD-RR-SC MCHS), a Computational Fluid Dynamic (CFD) software such as ANSYS FLUENT 17.0 is used to solve three dimensional fluid flow and heat transfer equations according to this assumptions: (a) In the present study, fluid flow in all simulated geometry designs are continuum due to Knudsen number, (*Kn*) for the fluid flow is less than (10^{-3}) [21]; (b) For the continuum flow, Navier-Stokes equation and non-slip boundary condition are applicable; (c) Fluid is Newtonian and incompressible; (d) Due to microscopic size of channel and to prevent a high pressure drop, laminar flow is applied for all geometry; (e) Fluid flow and heat transfer are simulated in steady-state; (f) Constant thermophysical properties; (g) Viscous dissipation is neglected due to the highest pressure drop in present study is less than 1 MPa with considering the first law of thermodynamics; (h) Gravitational force and radiation heat transfer are neglected.

3.1 Governing Equations

Based on the assumptions that made in the present study, governing equation for conservation of mass, momentum and energy equations can be written as:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Where *u, v* and *w* are the velocity components in *x*, *y* and *z*-directions respectively.

Momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho_f}\frac{\partial p}{\partial x}+\frac{\mu_f}{\rho_f}(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho_f}\frac{\partial p}{\partial y}+\frac{\mu_f}{\rho_f}(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}) \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_f}\frac{\partial p}{\partial z}+\frac{\mu_f}{\rho_f}(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}) \tag{4}$$

Where ρ_f and μ_f are the density and dynamic viscosity of the working fluid(water), respectively, and *p* is the fluid(water) pressure. There have two energy equation that related to the present study such as energy equation for fluid region, Eq. (5) and energy equation for solid region, Eq. (6):

$$u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}+w\frac{\partial T_f}{\partial z}=\frac{k_f}{\rho_f c_{Pf}}(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}+\frac{\partial^2 T_f}{\partial z^2}) \tag{5}$$

$$0=k_s(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}+\frac{\partial^2 T_s}{\partial z^2}) \tag{6}$$

Where T_f, T_s, k_f, k_s and Cp_f are the fluid's temperature, solid's temperature, fluid thermal conductivity, solid thermal conductivity and fluid specific heat, respectively.

3.2 Boundary Condition

Boundary condition is a condition for hydrodynamic and thermal that we applied on the simulated geometries in the present study. Uniform velocity with the temperature of 300 K is applied on the inlet channel for all cases. While at the outlet, we set as atmospheric pressure. A uniform heat flux of 100W/cm^2 is applied on the substrate of the heat sink. At the fluid-solid interface, no-slip and no penetration are assumed. Table 2 shows the details for other boundary conditions.

Table 2
Boundary condition

Boundary	Location	Condition
Hydrodynamic	At the fluid-solid interface	No-slip and no penetration $u = v = w = 0$ $-k_s(\frac{\partial T_s}{\partial n}) = -k_f(\frac{\partial T_f}{\partial n})$ where n is the coordinate normal to the wall
	At inlet, $x = 0$	$u_f = u_{in}$ $v = w = 0$
	At outlet, $x = L_t = 10mm$	$p_f = p_{out} = 1atm$
Thermal	At inlet, $x = 0$	$T_f = T_{in} = 300K$ (for water) $-k_s(\frac{\partial T_s}{\partial x}) = 0$ (for solid)
	At outlet, $x = L_t = 10mm$	$-k_f(\frac{\partial T_f}{\partial x}) = 0$ (for water) $-k_s(\frac{\partial T_s}{\partial x}) = 0$ (for solid)
	At top wall, $z = Ht = 0.4mm$	$u = v = w = 0$ $-k_s(\frac{\partial T_s}{\partial z}) = 0$
	At bottom wall, $z = 0$	$-k_s(\frac{\partial T_s}{\partial z}) = q = 100W/cm^2$
	At side wall, $y = 0$	$\frac{\partial}{\partial y} = 0$ (symmetry)
	At side wall, $y = Wt = 0.3mm$	$\frac{\partial}{\partial y} = 0$ (symmetry)

3.3 Entropy Generation Analysis

Entropy generation analysis was conducted in order to measure the fluid flow and heat transfer irreversibility in the proposed microchannel heat sink. In this study, the irreversibility (entropy generation) was defined by two part, namely, entropy generation due to friction lost $\dot{S}'''_{gen,\Delta p}$ and entropy generation due to heat transfer $\dot{S}'''_{gen,\Delta T}$ as written in Eq. 13 and Eq. 14, respectively. Total entropy generation was calculated by Eq. (15) [22].

$$\dot{S}'''_{gen,\Delta p} = \frac{\mu}{T_f}\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial v}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2\right\} \tag{13}$$

$$\dot{S}'''_{gen,\Delta T} = \frac{\lambda_f}{T_f^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] \tag{14}$$

$$\dot{S}'''_{gen} = \dot{S}'''_{gen,\Delta p} + \dot{S}'''_{gen,\Delta T} \tag{15}$$

u, v and w are the velocity component in x-direction, y-direction and z-direction, respectively. Eq. (13) and Eq. (14) were integrated over fluid domain, (Ω) and rewritten as:

$$\dot{S}'''_{gen,\Delta p} = \iiint_{\Omega} \dot{S}'''_{gen,\Delta p}\, dV = \frac{\dot{m}}{\rho T_f} \Delta p \tag{16}$$

$$\dot{S}'''_{gen,\Delta T} = \iiint_{\Omega} \dot{S}'''_{gen,\Delta T}\, dV = \frac{Q(T_w - T_f)}{T_f T_w} = \frac{q_w A_{film}(T_w - T_f)}{T_f T_w} \tag{17}$$

$$\dot{S}'''_{gen} = \dot{S}'''_{gen,\Delta p} + \dot{S}'''_{gen,\Delta T} = \frac{\dot{m}}{\rho T_f} \Delta p + \frac{q_w A_{film}(T_w - T_f)}{T_f T_w} \tag{18}$$

V and $\dot{m}$ are the fluid volume and mass flowrate, respectively. Overall performance of enhanced microchannel heat sink was determined based on theory of entropy generation where it can be evaluated by Eq. (19).

Entropy generation in enhanced microchannel heat sink is labelled as $\dot{S}_{gen}$ while entropy generation in reference design (CR MCHS) is labelled as $\dot{S}_{gen,o}$. if the value of $N_{s,a}$ is less than 1, means that the enhanced designs have a better overall performance than conventional designs and dominates a pressure drop in the enhanced microchannel heat sink. This condition is vice versa for the value that greater than 1.

$$N_{s,a} = \frac{\dot{S}_{gen}}{\dot{S}_{gen,o}} \tag{19}$$

4. Discussion

Figure 7 and Figure 8 shows entropy generations due to friction lost, $\dot{S}'''_{gen,\Delta p}$ and heat transfer, $\dot{S}'''_{gen,\Delta T}$ in all microchannel heat sinks, respectively. As shown in Figure 7, entropy generation due to friction factor, $\dot{S}'''_{gen,\Delta p}$ of all designs increases with Re number. This is because pressure drop in the designs increase with Re number especially in RR MCHS due to blocking effect that provided by ribs geometry at the central portion of RR MCHS. Due to absence of blocking effect by ribs geometry, CR MCHS and SD MCHS obtained the lowest $\dot{S}'''_{gen,\Delta p}$ for all Re numbers. While hybrid microchannel heat sinks such as SD-RR MCHS and SD-RR-SC exhibit slightly higher than CR MCHS and SD MCHS but lower than RR MCHS.

As illustrated in Figure 8, entropy generation in all microchannel heat sinks are affected by heat transfer than friction lost. Figure 8 shows that, when Re number increases, $\dot{S}'''_{gen,\Delta T}$ decreases for all designs. It is attributed to the reduction of temperature difference between channel wall and fluid temperature. Furthermore, the figure reveals that, the proposed design (SD-RR-SC MCHS) obtains the lowest $\dot{S}'''_{gen,\Delta T}$ for all Re number. It can be seen that, combination of Sinusoidal cavities, Ribs and Secondary channel geometry could increase the flow mixing in microchannel heat sinks.

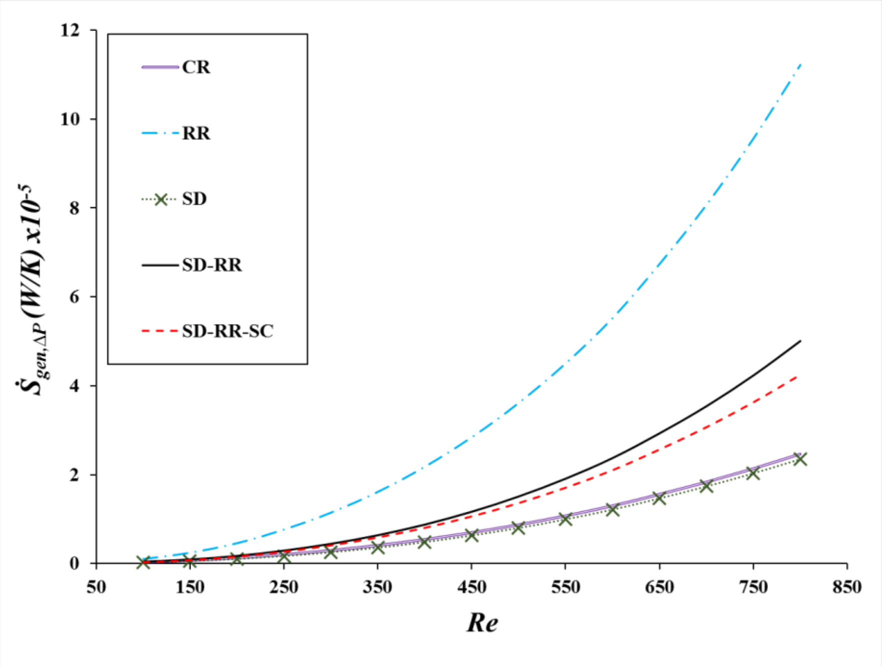

Fig. 7. Entropy generation due to friction loss

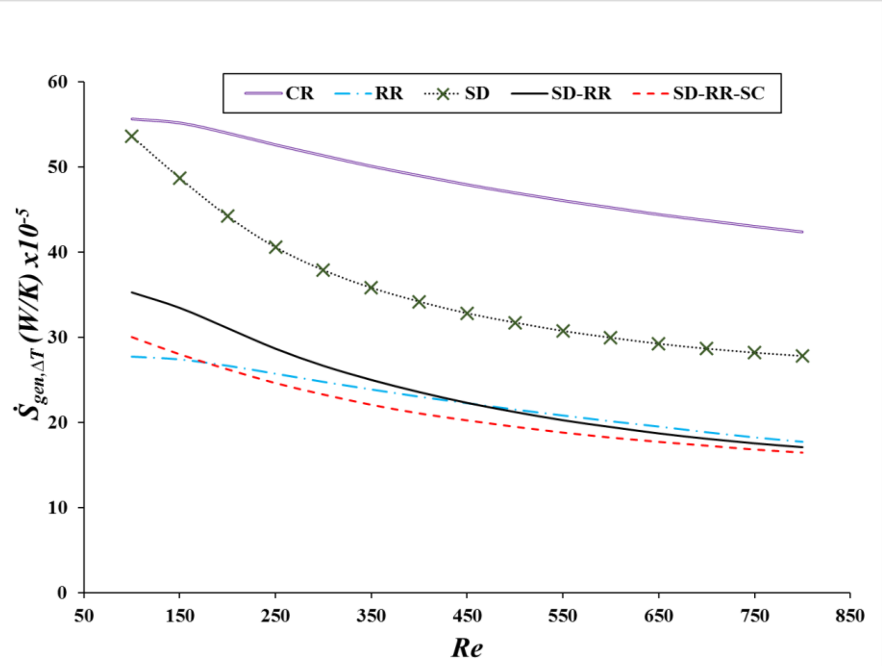

Fig. 8. Entropy generation due to heat transfer

Figure 9 shows Augmentation entropy generation number of all enhanced microchannel heat sink. The Figure illustrates that, SD MCHS obtains the highest $N_{s,a}$ at low Re number (100≤Re≤550) due to high thermal resistance that created by velocity gradient in the SD MCHS. By comparing all enhanced microchannel heat sinks, the proposed design (SD-RR-SC MCHS) exhibits the lowest $N_{s,a}$ compared to other designs for the most Re number. The optimum condition to achieve the lowest $N_{s,a}$ (0.43) is at Re number of 500.

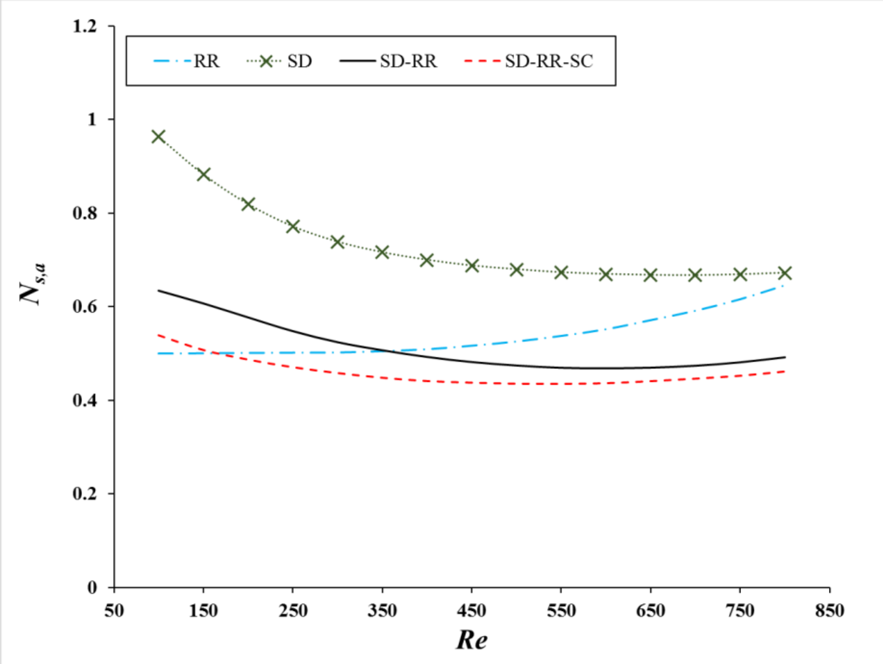

Fig. 9. Augmentation entropy generation number of all enhanced microchannel heat sink

5. Conclusion

In the present study, Entropy Generation Minimization method are used in order to analyse the capability of secondary channel geometry to reduce entropy generation in hybrid microchannel heat sink, SD-RR-SC MCHS. The objectives of this paper are twofold, namely, to analyse the effect of secondary channel geometry on fluid flow and heat transfer irreversibility, and to find the optimum overall performance from the view point of entropy generation minimization. The main findings are summarized as follows:

1) Secondary channel geometry in SD-RR-SC MCHS was more effective to reduce heat transfer irreversibility than fluid flow irreversibility due to increase in surface area provided by the secondary channel geometry.
2) By comparing SD-RR MCHS and SD-RR-SC MCHS, the existence of secondary channel geometry was more effective to reduce fluid flow irreversibility at the higher Re number.
3) By considering both fluid flow and heat transfer irreversibility, the optimum overall performance can be achieved at Re number of 500 with $N_{s,a}$ = 0.43.

Secondary channel geometry gives a great impact on thermodynamic efficiency in proposed design, SD-RR-SC MCHS due to reduction of entropy generation especially at the lower range of Re number. Means that, optimum overall performance can be achieved with the less pumping power consumption which it is good for the feature device that required a cooling device with low power consumption.

Acknowledgments
Authors wish to thanks Universiti Teknologi Malaysia for supporting this research activity under Takasago grant (R.K130000.7343.4B365).

References

[1] Sidik, Nor Azwadi Che, Muhammad Noor Afiq Witri Muhamad, Wan Mohd Arif Aziz Japar, and Zainudin A. Rasid. "An overview of passive techniques for heat transfer augmentation in microchannel heat sink." *International Communications in Heat and Mass Transfer* 88 (2017): 74-83.

[2] Black, James R. "Electromigration—A brief survey and some recent results." *IEEE Transactions on Electron Devices* 16, no. 4 (1969): 338-347.

[3] Ghani, Ihsan Ali, Nor Azwadi Che Sidik, and Natrah Kamaruzaman. "Hydrothermal performance of microchannel heat sink: The effect of channel design." *International Journal of Heat and Mass Transfer* 107 (2017): 21-44.

[4] Farsad, E., S. P. Abbasi, M. S. Zabihi, and J. Sabbaghzadeh. "Numerical simulation of heat transfer in a micro channel heat sinks using nanofluids." *Heat and Mass Transfer* 47, no. 4 (2011): 479-490.

[5] Qin, Yap Zi, Amer Nordin Darus, Nor Azwadi Che Sidik and Nor Azwadi. "Numerical analysis on natural convection heat transfer of a heat sink with cylindrical pin fin." *J. Adv. Res. Fluid Mech. Therm. Sci* 2, no. 1 (2014): 13-22.

[6] Razali, A. A., and A. Sadikin. "CFD simulation study on pressure drop and velocity across single flow microchannel heat sink." *J. Adv. Res. Des* 8, no. 1 (2015): 12-21.

[7] Wan Mohd. Arif Aziz Japar, Nor Azwadi Che Sidik, and M'hamed Beriache. "Hydrothermal Performance in a New Designed Hybrid Microchannel Heat Sink with Optimum Secondary Channel Geometry Parameter: Numerical and Experimental Studies." *J. Adv. Res. Des* 54, no. 1 (2019): 13-27.

[8] AbuBakar, Saidu Bello, Nor Azwadi Che Sidik, and Hong Wei Xian. "Numerical prediction of laminar nanofluid flow in rectangular microchannel." *Journal of Advanced Research Design* 50, no. 1 (2014): 1-17.

[9] Abubakar, S., CS Nor Azwadi, and A. Ahmad. "The use of Fe3O4-H2O4 nanofluid for heat transfer enhancement in rectangular microchannel heatsink." *J. Adv. Res. Mater. Sci.* 23, no. 1 (2016): 15-24.

[10] Zainal, S., C. Tan, C. J. Sian, and T. J. Siang. "ANSYS simulation for Ag/HEG hybrid nanofluid in turbulent circular pipe." *Journal of Advanced Research in Applied Mechanics* 23, no. 1 (2016): 20-35.

[11] Mugilan, Thillai, Nor Azwadi Che Sidik, and Wan Mohd Arif Aziz Japar. "The use of smart material of nanofluid for heat transfer enhancement in microtube with helically spiral rib and groove." *J. Adv. Res. Mater. Sci.* 32, no. 1 (2017): 1-12.

[12] Ny, G., N. Barom, S. Noraziman, and S. Yeow. "Numerical study on turbulent-forced convective heat transfer of Ag/Heg water nanofluid in pipe." *J. Adv. Res. Mater. Sci* 22, no. 1 (2016): 11-27.

[13] Hong, Fangjun, and Ping Cheng. "Three dimensional numerical analyses and optimization of offset strip-fin microchannel heat sinks." *International Communications in Heat and Mass Transfer* 36, no. 7 (2009): 651-656.

[14] Lee, Y. J., P. S. Lee, and S. K. Chou. "Enhanced thermal transport in microchannel using oblique fins." *Journal of Heat Transfer* 134, no. 10 (2012): 101901.

[15] Lee, Yong Jiun, Pawan K. Singh, and Poh Seng Lee. "Fluid flow and heat transfer investigations on enhanced microchannel heat sink using oblique fins with parametric study." *International Journal of Heat and Mass Transfer* 81 (2015): 325-336.

[16] Gong, Liang, and Bo Wei. "The Characteristics of Fluid Flow and Heat Transfer in Wavy, Dimple and Wavy-Dimple Microchannels." In *Applied Mechanics and Materials*, vol. 394, pp. 173-178. Trans Tech Publications, 2013.

[17] Li, Y. F., G. D. Xia, D. D. Ma, Y. T. Jia, and J. Wang. "Characteristics of laminar flow and heat transfer in microchannel heat sink with triangular cavities and rectangular ribs." *International Journal of Heat and Mass Transfer* 98 (2016): 17-28.

[18] Beng, Soo Weng, and Wan Mohd Arif Aziz Japar. "Numerical analysis of heat and fluid flow in microchannel heat sink with triangular cavities." *Journal of Advanced research in fluid mechanics and thermal sciences* 34, no. 1 (2017): 1-8.

[19] Japar, Wan Mohd Arif Aziz, Nor Azwadi Che Sidik, and Shabudin Mat. "A comprehensive study on heat transfer enhancement in microchannel heat sink with secondary channel." *International Communications in Heat and Mass Transfer* 99 (2018): 62-81.

[20] Japar, W. M. A. A., and N. A. C. Sidik. "The effectiveness of secondary channel on the performance of hybrid microchannel heat sink at low pumping power." In *IOP Conference Series: Materials Science and Engineering*, vol. 469, no. 1, p. 012032. IOP Publishing, 2019.

[21] Service, Robert F. "Coming soon: the pocket DNA sequencer." *Science (New York, NY)* 282, no. 5388 (1998): 399.

[22] Bejan, A. "Entropy Generation Minimization", CRC Press, Boca Raton, New York." (1996).