Paper ID: **370**

A Study on The Effect of Heat Transfer Within a Helical Shape Microchannel Heat Sink of Squared Cross-section

Mohammad Bahauddin Rakib(s)[1], Tanjila Akter(s)[1], HM Toufik Ahmed Zisan(s)[1, 2, *]
[1]Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh
[2]Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
**E-mail: toufik.zisan1602@gmail.com*

Abstract

A numerical simulation has been conducted considering a single-phase approach to designing a three-dimensional microchannel heat sink where two helical-shaped channels are in parallel configuration. Heat transfer nature and flow field behavior has been analyzed over a wide range of Reynolds numbers in terms of Nusselt number, dimensionless temperature profile, friction coefficient, and temperature contour. These results are then compared with those of conventional straight microchannel design. It has been determined that the frictional factor in the helical channel is 0.0883, which is more than that in straight channels of 0.06579, due to geometrical configurations for fluid flow at a lower Reynolds number of 500 for silicon as solid material. So, helical channels show higher pressure drops here, which limits the cost efficiency, but regardless of it, helical channels show more effectiveness than straight channels in terms of Nusselt number by 3 times the amount of conductive heat flux.

Keywords: Microchannel, Pressure drop, Heat transfer, Temperature.

1. Introduction

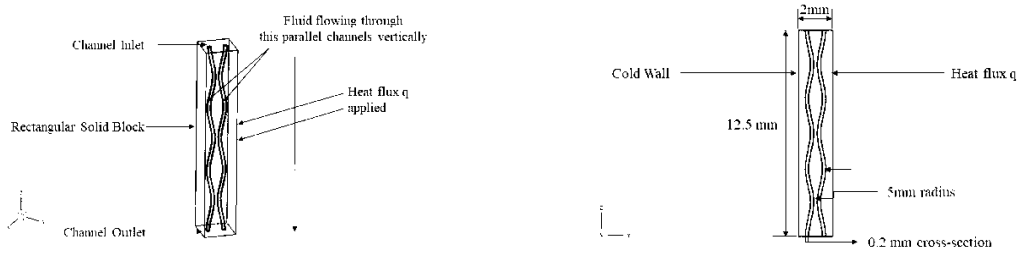
Microchannel heat sink is a cooling device used to prevent damage and increase the lifespan of electrical components in electric circuits because of the generation of high heat flux. There are most electronic devices that exist that show failure in operating at an elevated temperature, and the material in the devices has a thermal stress. There has always been a constraint in constructing effective microchannel heat sinks since fluid characteristics and heat reduction behaviors are dependent on too many variables such as pressure, temperature, drag, velocity, viscosity, and so on. So, a numerical simulation was performed using a single-phase approach to constructing a new three-dimensional microchannel heat sink with two helical-shaped channels in parallel configuration. Qu et al. [1] conducted conjugate heat transfer in a 3D rectangular microchannel using water as a fluid and silicon as a solid material. The result showed temperature rise, Nusselt number, and heat fluxes at the top, bottom, right, and left walls of channels. Mudawar et al. [2] also conducted heat transfer in a 3D rectangular microchannel numerically and experimentally to study pressure drop and compare both results. Chen et al. [3] conducted a numerical study on the inlet-outlet arrangement of different combinations such as I, N, S, D, U, and V shapes. It was found that fluid flowing vertically is more efficient than fluid flowing horizontally. Gunnasegaran et al. [4] found out the effect of geometrical parameters on three types of micro channels for a Reynolds number range of 100 – 1000 and showed rectangle cross sectional micro channels performed better than trapezoidal and triangular-cross sectional micro channels. Mohammed et al. [5] numerically investigated a wavy microchannel heat sink (WMCHS) with a rectangular cross-section of two dimensional to find out smaller pressure drop and increasing friction factor proportionally with amplitude of the channels. Kamaruzaman et al. [6] reviewed geometrical design parameters corrugated channels and flow disruption in MCHS for various channel shapes, such as sinusoidal wavy, zigzag, and convergent-divergent for efficient cooling. The result depicted a wavy MCHS with a sinusoidal shape that achieved a high heat transfer rate compared to other shapes with an acceptable pressure drop level. Sidik et al. [7] compared several types of channels and found the effect of surface roughness, fluid additives, and Reynolds number on the rate of heat transfer in a microchannel heat sink. Li et al. [8] experimented with different types of fins and cavities inside MCHS fluid flow to enhance heat transfer. They experimented with different orientations of fins and cavities. Targhi et al. [9] had discussed the geometric effects of MCHS on different types of zigzag arrangements. For this study, three aspects were considered: flow passage patterns, geometry of cross-sections, and inlet and outlet manifolds.

Therefore, this paper worked on two helical-shaped microchannels of squared cross section that are in parallel side by side because helical-shaped channels have a high surface area and resemble wavy-shaped channels, which have a higher efficiency than other channels [6]. These designs or shapes have been simulated numerically across Reynolds number 500 to 1500, and the results were compared with a conventional straight microchannel based on changing solid material to show the characteristics.

2. System Modeling

2.1. Physical Problem

Conjugate heat transfer in solid and liquid with laminar single-phase fluid flow is considered for this model. Geometrical model that has been designed for numerical investigation is Two helical wavy parallel micro channels of squared cross section side by side in a rectangular solid substrate block vertically. Here heat flux is applied at right side wall indicated in Fig. 1. Three different solid materials are used in this study i.e. Silicon, Copper, and Aluminum with water as fluid material. The geometric diagram are as follows:



(a) (b)

Fig. 1. (a) Isometric view with transparent rectangular block of helical shape parallel channels and (b) Right plane view with dimension of helical shape parallel channels.

From Fig. 1, Z-axis is chosen in vertical direction to choose channel and block height. X-axis and Y-axis are chosen for width and depth respectively.

Table 1. Geometric parameters

Block Width (mm)	Block Depth (mm)	Block Height (mm)	Channel width (μm)	Channel Depth (μm)	D_h (μm)	Pitch of helix	Amplitude (mm)	Heat Flux (W/cm^2)
2	2	12.5	200	200	200	5	0.1	90

2.2. Governing Equations

Heat is conducting from the block wall to the microchannel wall. Its governing equation is as follows:

$$Q_{conduction} = -kA\left(-\frac{dT}{dx}\right) \tag{1}$$

Here, incompressible, single phase and steady flow is considered for the problem. Governing equations for the present problem are as follows:
Continuity:

$$\nabla \cdot v = 0 \tag{2}$$

Momentum Equation:

$$\frac{\partial v}{\partial t} + (v \cdot \nabla)v = -\frac{1}{\rho}\nabla p + \mu\nabla^2 v + f + \rho g\beta(T - T_\infty) \tag{3}$$

Energy Equation:

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q + \mu\phi \tag{4}$$

2.3. Boundary Conditions

Table 2. Boundary conditions [10]

Boundary	Fluid flow condition	Thermal condition
Inlet/Inflow	$u = -U_o n$; Where $U_o = Re$*υ/(ρ*2e-4) m/s	$-n \cdot q = \rho \Delta H u \cdot n$ $\Delta H = \int_{T_{upstream}}^{T} C_p dT$; T_{ustr} = 293.15 K
Outlet/Outflow	$p_{hydro} = \rho_{ref} g \cdot (r - r_{ref})$ $[pl + K]n = -(\hat{p}_o + p_{hydro})n$; $\hat{p}_o \le p_o$ P_o = 101325 Pa	$-n \cdot q = 0$; Stationary
Wall/ Thermal Insulation	U = 0; No slip condition	$-n \cdot q = 0$; Stationary

2.4. Performance Parameters

To analyze the effect of channel configuration on heat transfer, various performance parametric equations [1] & [4] are used as follows

$$\text{Nusselt Number, } Nu = \frac{qD_h}{k_f \left(T_w - T_B\right)} \tag{5}$$

$$\text{Pressure Drop, } \Delta P = P_{inlet} - P_{outlet} \tag{6}$$

$$\text{Friction Factor, } f = \frac{2D_h \Delta p}{\rho u^2 L_c} \tag{7}$$

$$\text{Dimensionless Temperature Profile, } \theta = \frac{(T_B - 293.15)}{(T_W - 293.15)} \tag{8}$$

3. Computational Method

Finite element method is used in COMSOL Multiphysics to conduct numerical analysis. Here Galerkin FEM is applied in computational process. Tetrahedral three-dimensional mesh is generated for 208118 and 88999 number of nodes and elements respectively for the design model. Furthermore, grid independence test is conducted for different number of elements. With the consideration of time and machine capability, normal mesh size (element no. 69207) is chosen for the numerical investigation of helical shape micro channels.



(a) (b)

Fig. 2. (a) Three-Dimensional View of Tetrahedral Mesh Structure and (b) Results for grid independence test.

For validation numerical simulation is performed based on the work of Qu et al. [1] of heat transfer in three-dimensional rectangular Cross section. Qu et al. [1] conducted conjugate heat transfer in a 3D rectangular microchannel using water as a fluid passing through the channel horizontally and silicon as a solid material ,the heat flux only passing through the one side of the block, others surfaces kept insulated. CFD analysis was performed with some assumptions and boundary conditions. To validate the present studies method, exact similar geometrical configuration, same heat flux direction, same boundary conditions are being applied here and the comparative results are shown in Fig. 3. A recreation of the work of Qu et al. [1] shows a close similarity to the previously published result. This signifies accuracy of the present model.



(a) (b)

Fig. 3. Validation of the present model against the work of Qu et al. [1] for variation of temperature along length in mm for (a) channel top wall and (b) channel bottom wall.

4. Results and Analysis

Performance parameters, such as temperature contour, dimensionless temperature profile, friction factor, and Nusselt number, are presented here to study and compare helical and straight channels at Reynolds numbers 500–1500, following the application of the finite element approach. Here, the performance characteristics of three extremely conductive solid materials Silicon, Copper, and Aluminum are examined to assess how well they transfer heat across helical and straight channels respectively.

4.1. Temperature Contour

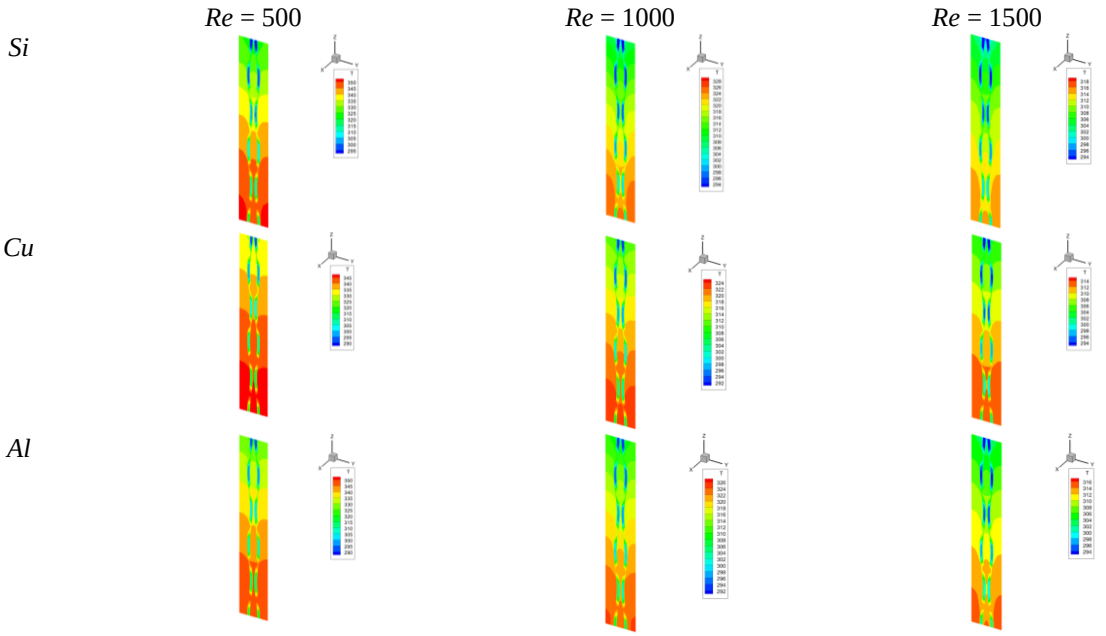


Fig. 4. Temperature contour of two helical channels in parallel configuration design with silicon, copper and aluminum as solid and water as fluid materials with varying Reynolds number.

With an increasing Reynolds number, the channels develop thermal boundary layer thickness much later than lower Reynolds number. The flows get disrupted because of the geometrical shape, which enhances the frictional effect and pressure pulses. The slower the fluid reaches constant temperature, the higher the heat transfer rate will be.

4.2. Dimensionless Temperature Profile



(a) (b)

Fig. 5. Dimensionless temperature profile with Reynolds number for (a) helical channels and (b) straight channels.

This result depicts a clearer picture of the fluid temperature rise and heat dissipation capabilities of solid materials. For both types of channels, silicon has lowest dimensionless temperature profile which shows better heat dissipation capability. The dimensionless temperature profile of silicon is 0.493 in helical channels and 0.408 in straight channels at Reynolds number 500. The dimensionless temperature profile for silicon is 0.455 in helical channels and 0.296 in straight channels at Reynolds number 1500. As Reynolds number increases, dimensionless temperature profile decreases so higher Reynolds number is preferable for better heat dissipation for both channels.

4.3. Friction Factor



(a) (b)

Fig. 6. Variation of friction factor with Reynolds number for (a) helical channels and (b) straight channels.

In helical channel fluid flows direction undergoes sudden change because of geometrical shape, which increases frictional effect between the interface of solid and fluid materials, whereas the streamline of fluid flows in straight channels don't get to meet any disruption. The frictional factor for silicon is 0.0883 in helical channels and 0.06579 in straight channels at Reynolds number 500, as can be seen in Fig. 6. As frictional factor rises, the pressure drop also rises which require more pumping work at outlet of the channels so it's not required. At Reynolds number 1500, the frictional factor decreases and for silicon it is 0.06286 in helical and is 0.03717 in straight channel which is lower than that at lower Reynolds number.

4.4. Nusselt Number

For Convective Heat Flux-



(a) (b)

Fig. 7. Variation of Nusselt number with Reynolds number considering normal convective heat flux for (a) helical channels and (b) straight channels.

For Conductive Heat Flux-



Fig. 8. Variation of Nusselt number with Reynolds number considering normal conductive heat flux for (a) helical channels and (b) straight channels

With an increasing Reynolds number, the Nusselt number also increases because the fluid reaches constant temperature slowly at a higher Reynolds number, which enhances its heat transfer property effectively. By analyzing normal convective flux helical shape micro channels yields a large value of Nusselt number compared to that of straight channels. Nusselt number for conductive heat flux for all materials are around 130 in helical whereas depicts 75 in straight channels at Reynolds number 500. Furthermore, by calculating normal conductive flux, the average Nusselt number is thrice than that of straight channels. In case of normal conductive flux, the effect of material is negligible for both channels. Moreover, copper shows better performance in case of normal convective flux.

5. Conclusion and Future Works

A numerical simulation was carried out on a microchannel heat sink based on heat transfer and fluid flow. Considering factors like temperature contour, friction factor, and Nusselt number, a helical-shaped channel shows far better performance than straight channel designs. The high friction factor which dominantly drops pressure in a helical-shaped channel is highly counterbalanced by the effect of heat transfer and Nusselt number. In this study, helical channels exhibit effective heat transfer, a dimensionless temperature profile of 0.493 to 0.455, higher frictional factor of 0.0883 to 0.06579, and a greater Nusselt number of 130 to 325 at Reynolds numbers ranging from 500 to 1500 comparing to straight channels. Based on heat transfer and Nusselt number and by trading off friction factor, helical channel performs way better than straight channel.

6. References

[1] W. Qu and I. Mudawar, “Analysis of three-dimensional heat transfer in micro-channel heat sinks,” *Int. J. Heat Mass Transf.*, vol. 45, no. 19, pp. 3973–3985, 2002, doi: 10.1016/S0017-9310(02)00101-1.

[2] W. Qu and I. Mudawar, “Experimental and numerical study of pressure drop and heat transfer in a single-phase micro-channel heat sink,” *Int. J. Heat Mass Transf.*, vol. 45, no. 12, pp. 2549–2565, 2002, doi: 10.1016/S0017-9310(01)00337-4.

[3] R. Chein and J. Chen, “Numerical study of the inlet/outlet arrangement effect on microchannel heat sink performance,” *Int. J. Therm. Sci.*, vol. 48, no. 8, pp. 1627–1638, 2009, doi: 10.1016/j.ijthermalsci.2008.12.019.

[4] P. Gunnasegaran, H. A. Mohammed, N. H. Shuaib, and R. Saidur, “The effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes,” *Int. Commun. Heat Mass Transf.*, vol. 37, no. 8, pp. 1078–1086, 2010, doi: 10.1016/j.icheatmasstransfer.2010.06.014.

[5] H. A. Mohammed, P. Gunnasegaran, and N. H. Shuaib, “Numerical simulation of heat transfer enhancement in wavy microchannel heat sink,” *Int. Commun. Heat Mass Transf.*, vol. 38, no. 1, pp. 63–68, 2011, doi: 10.1016/j.icheatmasstransfer.2010.09.012.

[6] I. A. Ghani, N. A. C. Sidik, and N. Kamaruzaman, “Hydrothermal performance of microchannel heat sink: The effect of channel design,” *Int. J. Heat Mass Transf.*, vol. 107, pp. 21–44, 2017, doi: 10.1016/j.ijheatmasstransfer.2016.11.031.

[7] N. A. C. Sidik, M. N. A. W. Muhamad, W. M. A. A. Japar, and Z. A. Rasid, “An overview of passive techniques for heat transfer augmentation in microchannel heat sink,” *Int. Commun. Heat Mass Transf.*, vol. 88, pp. 74–83, 2017, doi: 10.1016/j.icheatmasstransfer.2017.08.009.

[8] Y. Li, G. Xia, Y. Jia, D. Ma, B. Cai, and J. Wang, “Effect of geometric configuration on the laminar flow and heat transfer in microchannel heat sinks with cavities and fins,” *Numer. Heat Transf. Part A Appl.*, vol. 71, no. 5, pp. 528–546, 2017, doi: 10.1080/10407782.2016.1277940.

[9] Y. Alihosseini, M. Zabetian Targhi, M. M. Heyhat, and N. Ghorbani, “Effect of a micro heat sink geometric design on thermo-hydraulic performance: A review,” *Appl. Therm. Eng.*, vol. 170, no. September 2019, p. 114974, 2020, doi: 10.1016/j.applthermaleng.2020.114974.

[10] C. Multiphysics, “CFD Module User ’s Guide,” *COMSOL Multiphysics*, p. 598, 2016, [Online]. Available: https://doc.comsol.com/5.3/doc/com.comsol.help.cfd/CFDModuleUsersGuide.pdf