Numerical Investigation of Single-Phase Heat Transfer in Converging and Diverging Microchannel

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Abstract. Miniaturization of electronics has been the new trend in recent times. This has resulted in an exponential increase of heat flux and hence demands novel cooling methods. Insufficient cooling results into degraded performance, reduced power and, in the long run, may result in device failure. Microchannel cooling technology, due to its several advantages/challenges has been the central point of many researchers in the field of electronics cooling. The current paper concentrates on the investigation of single-phase heat transfer characteristics in converging and diverging microchannel. The numerical investigation of converging and diverging microchannel has been performed using commercially available solver ANSYS FLUENT. The heat transfer coefficient, Nusselt number, and outlet temperature were monitored for the various combinations of converging and diverging microchannels. Also, the results have been compared with a straight microchannel. It was observed that for the Reynolds number ranging from 250-1000 converging microchannels showed a higher value of heat transfer coefficient than the straight channel. Also, it was found that the heat transfer coefficient was directly proportional to the slope of convergence. The value of h was 10491 W/m²K for the slope of m=5×10⁻³. The results for diverging microchannel have also been extensively tabulated in the paper. It was also noticed that the pumping power was reduced in diverging microchannels when compared to a straight channel.

1. Introduction
The fluid flow through microchannel is one of the most efficient processes in heat exchange technology. At present, it is one of the key technologies in the field of chip cooling. Microchannel provides a high surface to volume ratio thus has a high heat transfer rate. The improvements of single-phase flow in microchannels can be divided into two aspects: heat transfer and fluid flow. The problem of obtaining a compact, high performance forced fluid cooling of planar IC was investigated by Tuckerman and Pease [1] in 1981. It was a pioneering experimental study in the field of microchannel heat transfer.

A review of microchannel heat exchangers was given by Goodling [2] in 1993. An experimental study with water as a coolant in microchannel heat exchangers was conducted by Peng et al [3] in 1994. They studied the heat transfer characteristics for the forced convection flow of water through rectangular microchannels. Channel hydraulic diameter was ranged from 133μm to 367μm and aspect ratios from 0.333 to 1. Reynolds number for the flow ranged from 200 to 1500. They developed the correlations for the Nusselt number and friction factor for the flow of water in the channel. It was also found that aspect ratio had a considerable effect on the heat transfer rate and pressure drop both in turbulent and laminar flows. Slowly the research began to shift towards the improvement of flow...
characteristics through surface and geometrical enhancement of microchannels. Kandlikar [5] in his paper of 2006 compares the single phase flow characteristics of water in plain microchannel and enhanced silicon microchannel with offset fin geometry. They employed flow restrictors at the inlet to act as physical pressure drop element. They developed a parameter called “pumping power coefficient” to evaluate the effectiveness of enhanced microchannels. It was found that the maximum COP for the plain microchannels is 11, whereas for the enhanced microchannel it was 290. Hence it was concluded that enhanced microchannel was more effective at heat dissipation despite the increase in the pressure drop. With the availability of commercial solvers for CFD, in the early 21st century, slowly there were a few rising developments in the analytical studies of 2D and 3D fluid flow in microchannels. Varying geometry of the microchannels exposes varying amounts of effective heat transfer area. Thus geometry of the channel affects the pressure drop and heat transfer performance which was clearly shown by Shah and London [4]. Dharaiya et al [6] studied the entrance header effects in small microchannels. Numerical simulations for three dimensional model of microchannel using CFD software tool FLUENT were carried out. Chandra et al [7] studied single phase flow through a series of uniform microchannels connected via converging-diverging sections with and without throat. It was inferred that converging-diverging part without throat shows better performance over with throat configuration.

In the present work, converging/diverging microchannels have been considered for the study of its heat transfer behaviour. Constant heat flux boundary condition has been applied to the bottom wall. Extensive numerical analysis has been performed by varying the angle of convergence and divergence. The heat transfer coefficient for different cases has been tabulated. The results have been compared with straight rectangular microchannel.

2. Nomenclature

- \( a_i \) = height of the converging microchannel at inlet
- \( b_i \) = width of the converging microchannel at inlet
- \( a_o \) = height of the converging microchannel at outlet
- \( b_o \) = height of the converging microchannel at outlet
- \( L \) = length of the microchannel
- \( \alpha \) = aspect ratio = \([a/b]\)
- \( m \) = slope of convergence/divergence = \([a_i - a_o]/L\)
- \( \rho \) = density of the fluid
- \( \mu \) = dynamic viscosity
- \( \nu \) = total heat flux
- \( \text{D}_h \) = hydraulic diameter
- \( \text{Nu} \) = Nusselt number
- \( \text{Re} \) = Reynolds number
- \( \alpha \) = aspect ratio = \([a/b]\)
- \( \text{h} \) = heat transfer coefficient

3. Governing Equations

3.1. Continuity Equation
Assuming the flow to be steady and incompressible continuity equation becomes

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

(1)

3.2. Momentum Equation
Momentum equation for x-direction is given below (2). Similarly, it can be written for y and z directions.

\[
\frac{u}{\partial x} + \frac{v}{\partial y} + \frac{w}{\partial z} = \left( -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2(u) \right)
\]  

(2)
3.3. Energy Equation

The contributions from radiation and other volumetric heat sources are accounted by the source term $S_h$.

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\bar{\nu} (\rho E + p)) = \nabla \cdot (\kappa_{\text{eff}} \Delta T) + S_h$$  \hspace{1cm} (3)

4. Computational Domain and Numerical Procedure

The heat transfer and fluid flow in microchannels with varying cross sections are studied using commercially available CFD solver, ANSYS FLUENT. Water was considered as the working fluid. It enters the microchannel with a fully developed velocity profile. Figure 1 shows the geometry of the convergent/divergent microchannel used in the present study.

Temperature of 300 K was maintained at the inlet. Initially, numerical simulation was performed for a straight microchannel with constant heat flux boundary condition at the bottom wall and the obtained results were compared with the scheme proposed by Shah and London [4].

![Figure 1. Cross-sectional area of converging/diverging rectangular microchannel.](image)

Table 1. Comparison of Nu, from current numerical work with Shah and London [4].

| $\alpha$ (a/b) | Re | Nu[4] | Nu obtained |
|---------------|----|-------|-------------|
| 0.5           | 100| 3.744 | 3.8008      |

Then the divergence/convergence effects on the microchannel of various cross sections were investigated. This comparison helps us to appreciate the effect of convergence/divergence angle on the heat transfer characteristics in microchannels. Very fine mesh is created so that the heat transfer and fluid flow effects are more accurate. Hexa/Prism mesh scheme was used as a result of simple geometry. Each of the geometries possesses approximately $4 \times 10^6$ grid elements. To ensure the best mesh spacing, grid independence test was carried out for the present computational model. At the inlet, Reynolds number was varied from 100, 250, 500, 750, 1000 to maintain laminar flow through microchannels and the hydraulic diameter is constant for all cases. Pressure outlet and a heat flux of 50kW/m² were specified at the bottom wall. Side and top walls were given symmetry. To achieve steady state analysis, pressure-based solver was used for simulation. SIMPLE method was used to introduce pressure into the continuity equation. In order to predict the heat transfer effects, the energy equation was activated during the analysis. The simulations were performed for a convergence criterion of $10^{-6}$. The microchannels used for the current study are shown in Table 1.

Table 2. The dimensions of micro-channels used for the current study.

| Channel Type         | Inlet Dimension (b × a) (μm × μm) | Outlet Dimension (b × a) (μm × μm) | $m$ |
|----------------------|-----------------------------------|------------------------------------|-----|
| Straight             | 500×400                           | 500×400                            | 0   |
| Converging/ Diverging (1) | 550×450                           | 450×350                            | 1   |
| Converging/ Diverging (2) | 600×500                           | 400×300                            | 2   |
Results and Discussions

This section explains the various results obtained by the numerical analysis which were performed across straight, converging & diverging microchannels. Also, it showcases various contours and graphs obtained for the different types of microchannel.

5.1. Validation of numerical model

Initially, the numerical results were validated for the rectangular straight channel with Shah and London [4]. Table 1 shows that the fully developed Nusselt number obtained from current numerical analysis is in good agreement with Nu obtained by Shah and London [4]. V.V. Dharaiya and S.G. Kandlikar [6] showed the variation of fully developed Nusselt number with different aspect ratio (α) of the rectangular microchannel. Figure 2 shows that the numerical model used to predict Nu for one wall constant heat flux in current work is in good agreement to values obtained by V. V. Dharaiya and S. G. Kandlikar [6].

5.2. Effect of convergence on heat transfer coefficient (h) for a rectangular microchannel

The effect of slope of convergence on heat transfer coefficient has been investigated thoroughly for rectangular shaped microchannel. Hydraulic diameter of 450μm has been considered and a constant heat flux of 50kW/m² was maintained at the bottom wall. The velocity at the inlet was varied from 0.2 to 2.2 m/s and the heat transfer coefficient was obtained for every case. The results of heat transfer coefficient for the straight channel were compared with converging microchannel of slope 1×10⁻³. It can be clearly observed from figure 3 that h is considerably higher for the converging channel compared to the straight channel. Further numerical analysis were performed to confirm the increase of heat transfer coefficient in converging microchannels. An extensive study has been carried out for the converging microchannel by varying the slope and observing its effect over heat transfer coefficient.

5.3. Effect of slope of convergence (m) on heat transfer coefficient (h)

Various converging microchannels (Table 2) were considered in the current study and for every case, heat transfer coefficient was tabulated for different Re values. Figure 4 infers that h increases as Re
increases for all converging microchannels. Also, the common trend that can be observed from figure 4 that converging channels show a higher value of heat transfer coefficient over the straight microchannel. It can be observed in figure 5 that the heat transfer coefficient is increasing linearly with increase in slope of the converging microchannel. Also, the best fit curve has been shown in figure 5. Figure 7 depicts the variation of h with slope of convergence, which shows that h increases with increase in Reynolds number. It was inferred that as the cross-section of the channel decreases along the length of the channel, the velocity of the liquid flow increases in order to maintain a constant flow rate. This is in accordance with the principle of conservation of mass. Since h is directly dependent upon the velocity gradient (Figure 9) of the fluid flow, there is an overall increase in the heat transfer coefficient and pressure drop for the converging microchannels. As the amount of convergence of the channel increases, so does the velocity of the flow to a greater amount, consequently causing the increase in h and pressure drop.

5.4. Comparison of converging and diverging microchannels

Figure 8 shows that there is a decrease in h for the diverging microchannel compared to straight and converging channels. This is because as the cross-sectional area of the channel increases, there is a decrease in the velocity along the channel length. This results in the decrease of pressure drop and heat transfer coefficient. Comparison of pressure drop for converging and diverging microchannels is shown in figure 6.
6. Conclusions
Following conclusions were drawn from the study:
- Converging microchannel has a better heat transfer coefficient compared to a straight channel both at low and high flow rates.
- At a given flow rate, the heat transfer coefficient can be increased by increasing the angle of convergence of the channel.
- Increasing the angle of convergence resulted in higher pressure drop along the channel, which results in increase in pumping power.
- Diverging microchannel had a lower heat transfer coefficient. Also, there was not much change in the heat transfer coefficient on increasing the divergence angle.
- Diverging microchannel had a lower pressure drop and hence lower pumping power was required.
- At very low flow rates (Re < 250) there is not much difference in the performance of straight and converging.

7. Future Work
Optimization of converging/diverging microchannel for a range of characteristic parameters and validating it with experimental data. The investigation of heat and flow characteristics in straight/converging/diverging microchannel in two phase flow are considered for the future work.

8. References
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