Numerical study of thermal performance with nanoparticles and grooves in Microchannel

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Abstract. The fluid flow and heat transfer characteristics for a laminar flow in a two-dimensional grooved microchannel has been numerically investigated. A suitable range of parameters such as Reynolds numbers, volume fraction, and groove offset are studied. The characteristics are investigated for various offsets in the grooved microchannel. The results specify an increase in heat transfer performance with increase in volume fraction, Reynolds number, and offset between upper and lower grooves. The offset 1 (δx=1) is found to be the most efficient groove arrangement with a high Nusselt number maintaining the least pressure drop coefficient.

1. Introduction
Efficient Heat transfer is required to keep the isolated small surface safe over the development of high heat. For this purpose, microchannel heat sink is used, over the last few decades. It is found that microchannel cooling techniques with air and liquid flow significantly improve the heat removal capacity of heat sink. Tuckerman and Pease [1] had experimented, where they detected a heat flux loss of seven hundred ninety watt with a decrease of approximately two bar pressure with the flow of water in microchannel made of silicon chips. Various studies have taken place to investigate the different parameters such as friction factor, pressure drop etc. in a rectangular microchannel [2-4]. Choi et al. [5] performed various observations for a large variety of Reynolds numbers twenty to twenty five thousands to develop a co-relation between Reynolds number and Nusselt number. Fedorov and Viskanta [6] stated that the microchannel heat sink having liquid flow has the improved results for cooling functions in electronics devices. Gamrat et al. [7] performed the study on rectangular microchannels taking in account of Navier–Stokes equation and reported that Navier–Stokes having energy equation can exactly estimate the thermal and flow characteristics in a microchannel fluid flow. Li and Peterson [8] numerically analysed three-dimensional heat flow in microchannels to get best channel shape and surface. They concluded the material of microchannel also plays an important role. Sasaki and Kishimoto [9] studied the influence of channel geometry on heat transfer. They performed numerical and experimental study of the parameters like channel dimension in various decreasing pressure condition; they derived an effective channel width for microchannels. Wu and Little [10]
performed experimental study on rectangular and trapezoidal MCHS at higher Reynolds numbers like eight hundred to thousands and observed that the turbulence in the flow enhances the heat transfer. A way to increase the heat transfer is by increasing the area of the unconfined fluid flow region. Creating the grooves in the microchannel flow path can be very useful for this purpose. Abouali and Baghernejhad [11] compared the rectangular and arc-shaped grooves on a microchannel for laminar flows and concluded that the arc grooves have higher heat flux removal. However, the pressure loss endured was not as significant, hence rectangular grooves have a better coefficient of performance.

Kuppusamy et al. [12] considered a triangular grooved microchannel for flow, where a substantial improvement in heat transfer was achieved through increasing the depth and groove angle. Further, Kuppusamy et al. [13] carried out the investigation and concluded that trapezoidal grooves have a better performance than triangular grooves. Alfaryjat et al. [14] concluded that the hexagonal crosssection of microchannel groove to have greater heat dissipation along with pressure drop over the rhombus and circular cross-section. Kumar [15] stated that the channels with trapezoidal grooves have outstanding advantages when compared to rectangular microchannels having twelve percent increase in heat transfer.

Recent studies show that the nanofluids have enhanced heat transfer rate than their corresponding base fluids [16-17]. Moreover, the enhancement in manufacturing, as well as the thermal fields have made it possible to make different types of microchannels and Nanofluids. These various nanofluids can be studied by dividing them into two categories, namely homogenous and multi-phase. Most studies available in the literature are performed on homogenous fluids. Maiga et al. [18] used water and Al$_2$O$_3$ as well as ethylene glycol and Al$_2$O$_3$ to increase the heat transfer rate in circular tube. Hung et al. [19] investigated the heat transfer in rectangular microchannel heat sink (MCHS) numerically. Selvakumar and Suresh [20] carried out experiments on a copper-based nanoparticle heat sink and have shown that the heat transfer increases of nearby thirty percent with 0.2 percentage of volume fraction of copper. Seif and Feizbakshi [21] carried a three-coordinate study on nanoparticles in a micro pin fin heat sink with alumina and copper oxide particles having convective flow. Better Nusselt number was obtained for the copper oxide nanoparticles when smaller copper particles were used. Ahmed et al. [22] examined the two-dimensional sinusoidal channel flow and found the rate of heat transfer grows with the increase of volume fraction of nanoparticles.

Mohammed et al. [23] examined the effects of various nanoparticles and nanofluids on the parameters of pressure drop and heat transfer rate across the channel. A microchannel heat sink of triangular shape was used. It has been examined that the gold and silver nanofluids give better heat transfer. Bayat and Nikseresht [24] compared various base fluids and observed that compared to water ethylene-glycol have improved heat transfer. The following work was carried out using two-phase modelling. Kalteh et al. [25] took the Eulerian-Eulerian approach to solve the case. He found that dual-phase method is more efficient over homogenous methods for modelling of nanofluids heat transfer. His study gave a linear gradual increase in coefficient of heat dissipation at the higher values Reynolds number and volume fraction of nanoparticles. Tahir and Mittal [26] used the Eulerian-Lagrangian method to solve the problem. Their study concluded linear gradual increase in heat transfer coefficient with a rise of Reynolds number and nanoparticles volume fraction.

With reference to listed literature, it is understood that size of nanoparticles, volume fraction, the geometry of the system, as well as the Reynolds number affects the performance and heat dissipation of the microchannel. In the current work, the effect of circular grooves and the offset between them on the heat dissipation is investigated on microchannel, along with the effect of the Reynolds number and the volume concentration. The changes due to the parameters on the pressure drop is also studied, and the performance of the microchannel is evaluated in terms of the coefficient of performance.
2. Numerical analysis

In the current work, an incompressible, laminar, steady-state, two-phase flow is considered in the microchannel. The flow is numerically modelled using the Eulerian-Eulerian approach, and the governing equations for the base liquid and the nanoparticle phases are given below.

Continuity Equation:
\[ \nabla \left( \rho_l \varphi_l \mathbf{V}_l \right) = 0 \] (1)
\[ \nabla \left( \rho_p \varphi_p \mathbf{V}_p \right) = 0 \] (2)

Where the volume fraction of base liquid and nanoparticles are related as,
\[ \varphi_l + \varphi_p = 1 \] (3)

Momentum equation:
\[ \nabla \left( \rho_l \varphi_l \mathbf{V}_l \mathbf{V}_l \right) = -\varphi_l \nabla p + \nabla \left( \varphi_l \mu_l \left( \nabla \mathbf{V}_l + \nabla \mathbf{V}_l^T \right) \right) \] (4)
\[ \nabla \left( \rho_p \varphi_p \mathbf{V}_p \mathbf{V}_p \right) = -\varphi_p \nabla p + \nabla \left( \varphi_p \mu_p \left( \nabla \mathbf{V}_p + \nabla \mathbf{V}_p^T \right) \right) \] (5)

Energy equations,
\[ \nabla \left( \rho_l \varphi_l c_p \mathbf{V}_l T_l \right) = \nabla \cdot \left( \varphi_l k_l \nabla T_l \right) - h_{lp} (T_l - T_p) \] (6)
\[ \nabla \left( \rho_p \varphi_p c_p \mathbf{V}_p T_p \right) = \nabla \cdot \left( \varphi_p k_p \nabla T_p \right) + h_{lp} (T_l - T_p) \] (7)

Where \( h_{lp} \) indicates interphase heat transfer coefficient, obtained using the Ranz-Marshall equation.

Non-dimensional Reynolds number, Nusselt number, and Pressure coefficient are defined below.
\[ Re = \frac{\varrho \mu \mathbf{V}_l}{\mu_l} \] (8)
\[ Nu = \frac{h_l k_l}{k_l} \] (9)
\[ \Delta P = \frac{\varrho \mathbf{V}_l^2}{\mu_l u_{in}^2} \] (10)

The coefficient of performance (\( C_p \)) can be defined as
\[ C_P = \frac{Nu}{\Delta P} \] (11)

Offset parameter (\( D_f \)) can be defined as,
\[ D_x = \frac{L_{of}}{d_i} \] (12)

The base geometry is a parallel plate microchannel, and the circular grooves are made on it, as shown in Fig 1. The height of the channel is 200 microns, and 100 times height is the length. Grooves with different diameter \( D_g \) and offset with different length \( L_g \) are made.
The thermal boundary conditions are that the inlet of fluid is at 293k, and the upper and lower walls are maintained at 303k. The outlet is kept as an outflow. The fluid then enters from the inlet at a constant velocity, along with the nanoparticles with a specified volume fraction. The volume fractions considered in the current study are 0.01, 0.03 and 0.05, and the Reynolds numbers considered are 100, 300 and 500 respectively. Three offset parameters, δx = 0, 0.5 and 1 are considered. Ansys Fluent® was used to solve the above governing equations numerically. The SIMPLE scheme was used for the pressure-velocity coupling, and the power-law scheme is used for discretizing the momentum and energy equations.

The mathematical model is validated by comparing with the experimentally obtained Nusselt number values [27], for a laminar nanofluidic flow in a two-dimensional un-grooved microchannel, and is shown in Table 2. A good agreement was found for both base fluid as well as nanofluid, at all the Reynolds numbers.

| Reynolds Number | Base Paper | Present Values | Deviation (%) | Nanofluid Type |
|-----------------|------------|----------------|---------------|----------------|
| 0.5             | 12.26      | 11.943         | 2.585644372   | Pure water     |
| 100             | 24.19      | 23.59          | 2.480363787   |                |
| 0.5             | 12.46      | 12.044         | 3.338683788   | Water + Al2O3  |
| 100             | 24.6       | 23.81          | 3.211382114   |                |
3. Result and Discussion
The heat transfer coefficient, pressure coefficient, and the coefficient of performance of Al₂O₃-water based grooved microchannels are obtained at various Reynolds numbers, particle volume fractions, and groove offsets, and the details are given below.

3.1 Pressure coefficient
The effect of volume fraction on the pressure coefficient as in Figure 3. It can be observed that with the rise in the nanoparticle’s volume concentration, there is a slight decrease in pressure drop for Re = 100. Offset 1 is seen to have the least pressure coefficient. Offset 0 has the maximum pressure loss for all the offsets considered. As the Reynolds number increases, the difference in the pressure coefficient decreases for all the offsets. The difference in the coefficient for offset 0.5 and 1 is minimal for higher Re numbers but offset 1 turns out to be the optimum in controlling the pressure loss.

3.2 Nusselt number
The temperature contours for different offset channels are depicted in Fig 5. The effect of offset is trivial, although offset 0 tends to showcase better heat transfer. Nusselt number rises linearly for the rise in Reynolds number for each geometry and the increment trend is similar but more effective in terms of ϕ, where more quantity of nanoparticles contributes to more effective convective heat transfer.

3.3 Coefficient of performance (CP)
Fig 4 depicts the dependence of the coefficient of performance on the above parameters. From the figure, it is evident that the rise in Reynolds number and volume concentration gives to a linear increase if CP and have a significant influence compared to the offset parameter. Also, at high Reynolds numbers, the increase in the CP value with offset is more significant, than at low Reynolds numbers. From this figure, it can be seen that Re 500, and offset 1 is the optimum groove arrangement.

![Figure 3](image-url)

Figure 3. Variation in pressure coefficient with offset, volume fraction and Reynolds number.
Figure 4. Variation in the coefficient of performance with offset, volume fraction and Reynolds number.
4. Conclusions

Heat dissipation and pressure drop in Al₂O₃-water based nanofluids investigated in a two-dimensional circular grooved microchannel. Eulerian–Eulerian approach is used to simulate the nanofluid flow, and heat transfer behaviour. Simulations are performed at several Reynolds numbers, particle volume fractions, and groove offsets. The following conclusions are made from this study.

- Numerical study show that the dimensionless pressure drop is decreasing with a rise in Reynolds number and not much dependent on the volume concentration and offset between the grooves. Although at lesser Reynolds number increment in offset reduces the pressure drop.
- The coefficient of performance is equally influenced by the increase in Reynolds number, volume fraction and offset between grooves. It increases with an increase in these parameters. Although with offset increment, the increase in it is considerably less.

Nomenclature

- \(c_p\) specific heat at constant pressure (J/kg K)
- \(d_p\) nanoparticle diameter (m)
- \(D_h\) hydraulic diameter (m)
- \(D_d\) diameter of groove (m)
- \(h\) heat transfer coefficient (W/m² K)
- \(H\) channel height (m)
- \(k\) thermal conductivity (W/m K)
- \(L\) channel length (m)
- \(L_o\) length between grooves (m)
- \(L_{of}\) length of the offset distance (m)
- \(Nu\) Nusselt number
- \(p\) pressure (Pa)
- \(\Delta P\) non-dimensional pressure
- \(Re\) Reynolds number
- \(u, v\) velocity components in the x and y directions, respectively (m/s)
- \(\vec{V}\) velocity vector (m/s)
- \(T\) temperature (K)

Greek Symbols:

- \(\rho\) density of fluid [kg/m³]
\( \mu \) viscosity of fluid \( \varphi \) volume concentration

Subscripts:

- \( i \) inlet
- \( l \) liquid phase
- \( p \) particle phase

5. References

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