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# The Flow Characteristics and Thermal Performance of Nanofluid in a Vertical Microchannel: A numerical study

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**Abstract**

Electronic cooling remains a challenge that requires further research and investigation due to the ever-higher heat flux. Microchannels are one of several high heat flux heat dissipation designs that meet this requirement. Nanofluids exhibit not only dramatically improved thermal conductivity, but also thermophysical properties that are strongly temperature- and size-dependent, which can be achieved by adding nanoparticles with diameters less than 100 nm to conventional liquid working fluids. increase. Nanofluids are expected to be used as coolants in microchannel heat sinks to achieve a double benefit in improving heat transfer and to meet the increasing cooling demands of electronic devices. The present work focus on the flow characteristics and enhancement of heat transfer in a vertical microchannel with a triangular microchannel using magnesium oxide water nanofluid. A wide range of volume fractions was tested in this work, the governing equations were solved using the finite volume technique. An external heat flux was applied on the three walls. The three-dimensional analysis showed that the increase in the volume fraction promoted the heat transfer remarkably, the water base fluid showed the lowest Nu number along the microchannel wall, while no penalty for the pressure drop was achieved with the increase in the volume fraction.

**Keywords:** *Heat Transfer, Nanofluid, Microchannels and Nusselt number.*

## 1. Introduction

Recent developments in automotive, aerospace and electronics technology are associated with continued reductions. Increased component size, increased power and heat generation. This requires an effective cooling strategy to maintain the safe and efficient operation of these components. Microchannels have been shown to have relatively high heat dissipation capacity better than traditional heat dissipation devices due to the large heat transfer area to the liquid volume relationship.

Since Choi [1] first introduced nanofluid, recent growths in nanofluid applications and the approaches for improving cooling technology for electronic devices with high heat applications have attracted the need for possible production of effective and compact cooling components.

The applications of microchannels are in increasing demand for their high heat flux, due to their advantages such as compactness, lightweight and high heat transfer surface area to fluid volume ratio in comparison to other macro-scale systems.

Kandlikar et al [2] classified channels based on flow considerations. They proposed that conventional channels are identified according to the hydraulic diameter as follows

Conventional Channels: Dh > 3 mm

Minichannels: 3 mm ≥ Dh > 200 μm

Microchannels: 200 μm ≥ Dh > 10 μm

Transitional Channels: 10 μm ≥ Dh > 0.1 μm

Transitional Microchannels: 10 μm ≥ Dh > 1 μm

Transitional Nanochannels: 1 μm ≥ Dh > 0.1 μm

Molecular Nanochannels: 0.1 μm ≥ Dh

Several works have been reported in the literature to study the microchannel with nanofluid as a working fluid. Salman et al [3] investigated numerically the enhancement of heat transfer of various nanofluids with micro-tube with constant heat flux. They concluded that the friction factor was not influenced by the volume fraction of the nanoparticle. The same authors [4] presented a numerical and experimental study for the forced laminar flow of nanofluids. They reported an enhancement in heat transfer rate by up to 22% compared to water-base fluid. However, the maximum deviation between the numerical and experimental in Nu number was found 10.5%.

Chai et al [5] presented a three-dimensional numerical investigation to study the laminar flow in an interrupted microchannel with different configurations. They reported an improvement in the heat transfer coefficient. They attributed this enhancement to the mixing of hot and cold water in the microchamber and the much higher redeveloping level of the thermal boundary layer in the microchannel areas. Moahmmadian et al [6] investigated numerically the single-phase heat transfer in the microchannel. They highlighted that increase in volume concentration increased the effectiveness and pumping power of the system. They also highlighted that the frictional contribution of entropy increased with the increase in Re number and volume fraction. A great deal of work was devoted to studying the flow microchannels using nanofluid, however, studies on using nanofluid in microchannels with triangular cross-section are still very limited.

Li et al [7] studied the mass flux and heat flux on the flow boiling in microchannels with and without triangular cavities. They conducted an experimental study and found that the triangular cavity in the microchannel showed a significant improvement in heat transfer. Zhao and Bi [8] tested the air-water two phase flow in vertical triangular microchannels, they recorded the image of two phase flow by a high-speed analyzer.

The impact of various nanofluids on triangular microchannel heat sink was investigated by Mohammed et al [9], who recommended that diamond-H2O and Ag-H2O to achieve the highest overall heat transfer enhancement. Shanjaian et al [10] presented a three-dimensional numerical simulation of a slip flow in a triangular microchannel, they revealed that the Re number is less important in the analysis.

The geometry of the triangular manifold and the dimensions of microchannels were analyzed numerically by Mohammadi et al [11], they highlighted that including a vertical spacing at the corner of manifolds is critical to achieving a high level of flow uniformity. The heat transfer and fluid flow of a nanofluid in a microchannel with various shape configurations were tested by Behnampour et al [12], the results suggested that the triangular form has the best thermal performance evaluation.

The present study aims to investigate the flow characteristics and the heat transfer performance in a vertical microchannel using MgO water nanofluid as a working fluid.

## 2. Methodology

The geometry studied in the present work is shown in Figure 1, the geometry tested is a vertical microchannel with a triangular cross-section area, the height of the microchannel is 2000 micrometer, and the lengths of the triangle are 200 micrometers each.

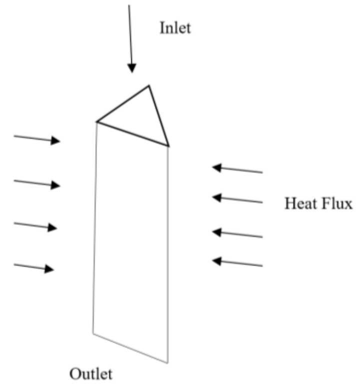


Figure 1 Microchannel Geometry

The governing equations were solved in the present study are continuity, momentum equation, and energy equation and can be written as

Continuity equation

$$\nabla(\rho\vec{v}) = 0 \quad (1)$$

Momentum equation

$$\nabla(\rho\vec{v})\vec{v} = -\nabla p + \nabla(\tau) + \rho g + F \quad (2)$$

Energy equation

$$\nabla(\vec{v}(\rho E + P)) = \nabla\left(K_{eff}\nabla T - \sum h_j J_j + (\tau\vec{v})\right) \quad (1)$$

The density of Nanofluid is expressed as:

$$\rho_{nf} = (1-\phi)\rho_f + \emptyset\rho_s \quad (2)$$

The specific heat of the nanofluid is expressed as:

$$C_{pnf} = \frac{(1-\phi)(\rho C_p)_f + \phi(\rho C_p)_s}{\rho_{nf}} \quad (3)$$

The thermal conductivity can be calculated as:

$$K_{eff} = K_f\left(\frac{K_s + 2K_f - 2\emptyset(K_f - k_s)}{K_s + 2K_f + \emptyset(K_f - k_s)}\right) \quad (4)$$

The effective viscosity is written as [1]:

$$\mu_{eff} = \mu_f(1 + 5\emptyset + 80\emptyset^2 + 160\emptyset^3) \qquad (5)$$

The heat transfer coefficient can be written as:

$$h = \frac{Q}{(T_H - T_C)} \qquad (6)$$

Nu number is calculated as:

$$Nu = \frac{hD}{K} \qquad (7)$$

Re number is expressed as:

$$\mathrm{Re} = \frac{\mathrm{UD\rho}}{\mu} \qquad (10)$$

The thermal properties of the nanoparticles are shown in table 1

**Table 1 Thermal properties of MgO nanoparticles**

| Nanoparticle | Density $Kg/m^3$ | Thermal conductivity $w.m^{-1}.k^{-1}$ | Specific heat $J.kg^{-1}.k^{-1}$ |
|---|---|---|---|
| **MgO** | 3450 | 9 | 880 |

## 3. The Numerical Procedure

The finite volume approach was used to solve the governing equations along with boundary condition. The domain was divided into 98400 cells and a quadratic upwind scheme was used to discretize all terms. The SIMPLEC algorithm was chosen to solve the pressure-velocity coupling equation. The convergence criterion is to reduce the maximum residual to less than $10^{-6}$. After solving the pertinent equations, all terms of flow dynamics can be determined.

The boundary conditions applied in the present test case are inlet velocity at 2 m/s at a constant temperature of 300 K, while the three wall are s kept at constant heat flux 20 $w/cm^2$, and the outlet pressure is zero gauge at the pipe exit.

## 4. Results and Discussion

In the present section, the results are introduced and discussed for the heat transfer enhancement, and the flow characteristics of Magnesium Oxide- nanofluid in a vertical microchannel subjected to an external heat flux of 25 w/cm$^2$.

The pressure drop was investigated and the results are shown in Figure 2. The pressure increases along the microchannel wall, however, no increase in the pressure with the increase in the volume fraction was noticed, this is in favour of adopting the nanofluid as a coolant.

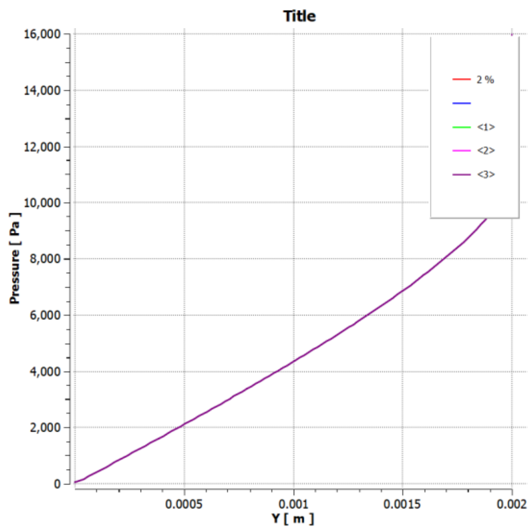


Figure 2 Variation of Pressure drop with volume fraction

The total enthalpy was also studied and the results are depicted in Figure 3. It can be seen from the Figure that the enthalpy drops sharply along the microchannel, in contrast, the enthalpy was found to decrease with the augmentation in the volume fraction.

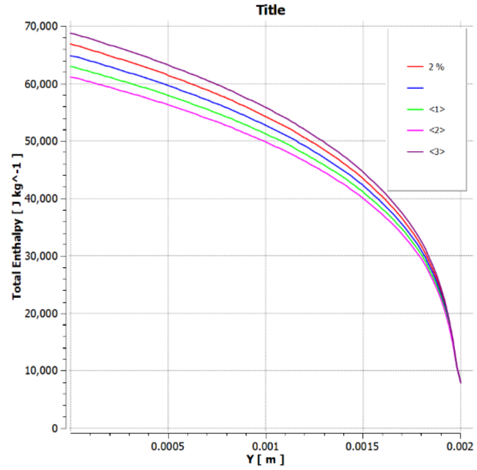


Figure 3 Variation of enthalpy with the volume fraction

The Nu number along the wall is studied, and the results are illustrated in Figure 4.

The Nu number drops sharply at the entrance of the microchannel until the flow becomes fully developed, at that point onward, the Nu number decreases slowly along the wall. Various volume fractions (2%, 4%, 6% and 8%) were tested as well as water, the influence of the volume fraction was studied and found that the increase in volume fraction is in favour of heat transfer. The average Nu number at the upstream wall was calculated for the different volume fractions, and the results are presented in Table 2.

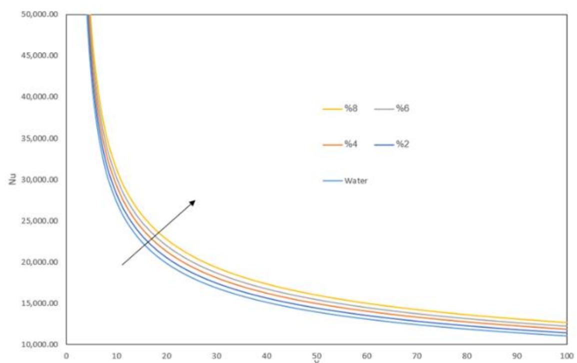


Figure 4 Nu variation at the wall

The variation of average Nu along the wall with volume fraction was calculated and introduced in table 2. It can be seen that the average Nu number is promoted significantly with the increase in nanoparticle volume fraction. The heat transfer improved by 4% at $\varphi$=2% compared to water, while this increase was 13% when the volume fraction jumped to 8%.

**Table 2 Variation of average Nu with volume fraction**

| Volume fraction ϕ | $Nu_{avg}$ |
|---|---|
| **Water** | $2.1 \times 10^4$ |
| **2%** | $2.18 \times 10^4$ |
| **4%** | $2.26 \times 10^4$ |
| **6%** | $2.34 \times 10^4$ |
| **8%** | $2.42 \times 10^4$ |

The temperature variation with volume fraction along the microchannel wall is calculated and the results are shown in Figure 5. It can be seen from the figure that the higher the volume fraction, the more the temperature along the wall. This is in line with the improvement in heat transfer due to the existence of the nanoparticles in the base fluid.

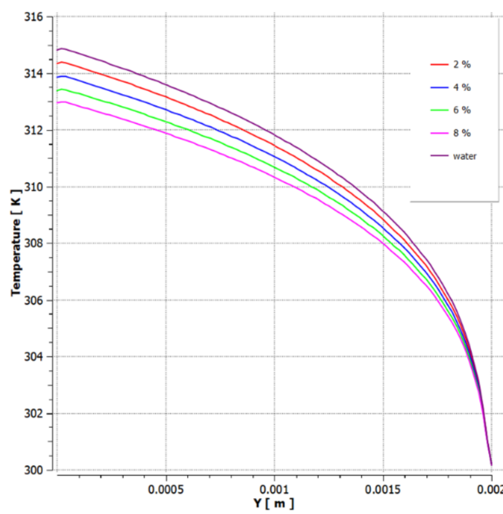


Figure 5 Variation of temperature with volume fraction along the microchannel

In order to give a better understanding of the heat performance, the vertical variation of the temperature in the microchannel was investigated and the results were depicted in Figure 6. The temperature profile reflects the heat flux applied on both triangle sides while the other sider kept adiabatic, the highest temperature value is at the top of the triangle and decreases gradually till 300 k which is the inlet boundary condition and increases again at both sides of the triangle due to the effect of the external heat flux. It is evident from the figure that the volume fraction 8% has the lowest temperature profile while water exhibited the higher temperature profile, this trend explains the heat exchange due to the higher thermal conductivity of the nanofluid.

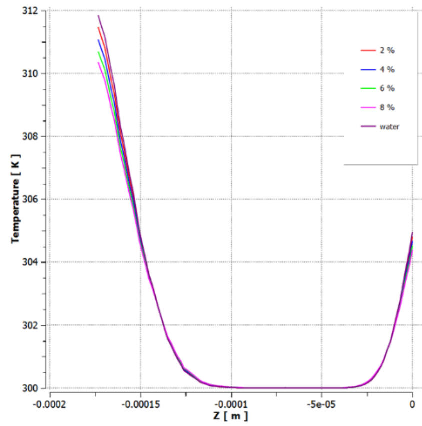


Figure 6 Variation of temperature with volume fraction on a vertical line in the middle of microchannel

In addition to increasing heat transfer rate, it is also recommended to minimize the change of entropy, the results of variation of entropy along the microchannel wall with various volume fraction are illustrated in Figure 7. The entropy declines gradually along the wall for all volume fractions tested in the present study, water showed the highest entropy variation, while the increase in the volume fraction resulted in decline in entropy, this trend is in agreement with heat enhancement with the increase in concentration of nanoparticle.

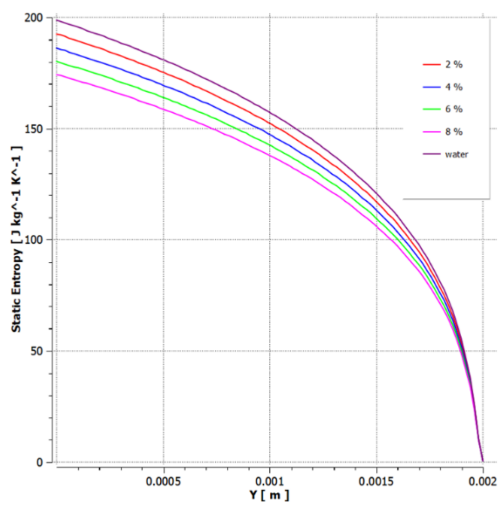


Figure 7 Entropy variation with the volume fraction along the microchannel

To understand the flow characteristics in the microchannel, the contours of velocity are depicted in Figure 8. It is clear the velocity is maximum at the centerline and minimum at the walls, the velocity

is constant at the fully developed flow where the Nu number change is almost negligible.
The variation of velocity across the microchannel was further investigated and the contours of velocity at various locations are introduced in Figure 8. The contours of the velocity show the change of velocity at 0.001, 0.001396, 0.001732, and 0.0001 micrometer, the velocity profile is evident at these different locations as the working fluid advances in the microchannel.

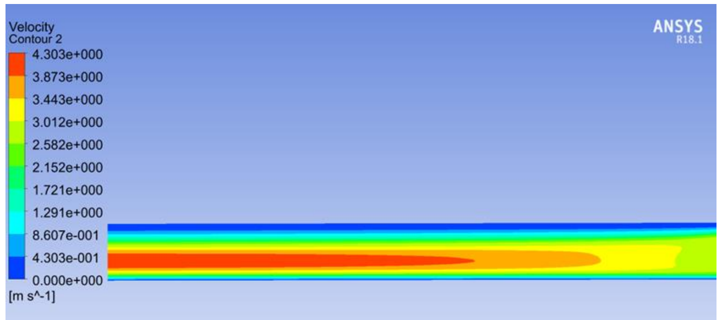


Figure 8 Velocity contour in a middle plane along the microchannel

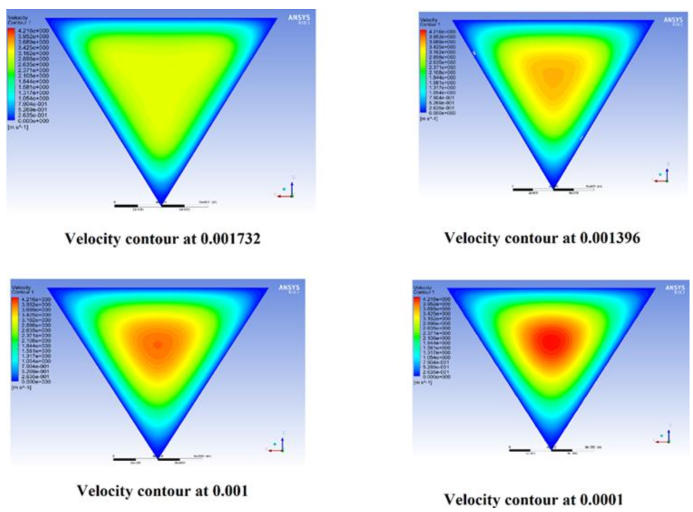


Figure 9 contours of velocity at various distances across the microchannel

## Conclusions

The heat transfer enhancement in a microchannel with triangular cross-section using Mg0 nanofluid is studied, the governing equations were solved numerically along with the boundary conditions using the finite volume approach by ANSYS Workbench V18 software, a range of volume fractions (2%- 8%) were tested as well as water. The following results were presented and discussed:

- The results showed that the increase in the volume fraction promoted heat transfer.
- The increase in volume fraction showed in substantial increase in the pressure drop
- Water showed a weak performance in terms of heat transfer among various concentrations tested.
- Average Nu number improved by 13% compared to water as a based fluid.

## Nomenclature

| | | |
|---|---|---|
| $C_p$ | Specific Heat at Constant Pressure | $KJ.kg^{-1}.k^{-1}$ |
| **D** | Diameter, Hydraulic diameter | m |
| **E** | Energy | J |
| **G** | Gravitational acceleration | $m.s^{-2}$ |
| **H** | Height | m |
| **H** | Heat transfer coefficient | $W/m^2K$ |
| **K** | Thermal conductivity | $W.m^{-1}.K^{-1}$ |
| **P** | Pressure | Pa |
| **Q** | Heat flux | $W/m^2$ |
| **S** | Entropy generation | $W/K.m^3$ |
| **T** | Temperature | K |
| **t** | Time | s |
| **V** | Volume | $m^3$ |
| **V** | Velocity (*u*, *v* ,*w*) | m/s |
| **x,y,z** | Coordinates | m |

**Subscripts**

| | | |
|---|---|---|
| **f** | Fluid | |
| **s** | Solid | |
| **np** | Nanoparticle | |
| **eff** | Effective | |
| **i** | Initial | |
| **in** | Inlet | |
| **out** | Outlet | |
| **Greek symbols** | | |
| **ϕ** | Volume fraction | |
| **μ** | Viscosity | Kg/m.s |
| **Ρ** | Density | $Kg/m^3$ |
| **Nu** | Nusselt Number | |

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