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Numerical Modelling of Nanofluid Based Microchannel Heat Sink

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Abstract: *The present paper describes the effect of heat transfer and fluid flow characteristics of rectangular microchannel under laminar flow conditions. Three dimensional model is created and simulated by applying suitable boundary conditions in the commercial CFD package ANSYS. Two microchannels with width 500 µm and 300 µm are considered for the present study. Water and nanofluid are chosen as working fluids. Two-phase mixture model is used for the modelling of microchannel working with nanofluid. Numerical model have been validated with the available experimental work in the literature. Then, the simulations were carried out for two different channels with nanofluid as working fluid. Heat transfer and flow characteristics of microchannels with nanofluid as working fluid have been obtained for different nanofluid volume concentrations. Finally, the comparison studies between water and nanofluid have been presented in order to understand the effective use of nanofluid as the heat transfer fluid.*

Keywords: Microchannel, Two-Phase Mixture Model, Nanofluids.

I. INTRODUCTION

Conventional cooling methods like air cooling are not sufficient to satisfy the increased cooling demands of sophisticated electronic equipment (Steinke & Kandlikar, 2006). The idea of microchannels heat sink was first instigated by Tuckerman and Pease (Tuckerman & Pease, n.d.) in 1981. Microchannels provide several advantages like compactness, light weight and large heat transfer surface area to fluid volume ratio which forge them more attractive (Lee, Garimella, & Liu, 2005). Kandalikar et al. (Steinke & Kandlikar, 2006) reviewed the possibilities of using channels with smaller dimensions and suggested the flow passage dimensions in convective heat transfer. Suresh et al. (Lee et al., 2005) performed experimental analysis to determine the validity of classical correlations based on conventionalized channels.

Nanofluid is prepared by suspending the nanometer-sized particles (nanoparticles) in the base fluid. In general, the nanoparticles are made up of metals, metal oxides, carbides, or carbon nanotubes. Wenhua and Routbort et al. (Yu, France, Routbort, & Choi, 2008) presented a review on the research and development in nanofluids for heat transfer applications. Routbort et al. (Routbort, Singh, Timofeeva, Yu, & France, 2011) studied the pumping power of nanofluid through a micro system. The addition of nanoparticles to the base fluid increases the viscosity. So, it requires more pumping power to drive the fluid through channels. Moreover, it improves thermal conductivity and heat transfer coefficient than the base fluid.

Several researchers have carried out nanofluid modelling using various approaches (single phase and two phase) and concluded that the two-phase approach gives the most accurate results. For example Nazififard et al. (Nazififard, Nematollahi, Jafarpur, & Suh, 2012) and Davarnejad et al.(Davarnejad, Barati, & Kooshki, 2013) worked on numerical simulation of Al_2O_3 nanofluids with different particle volume concentrations and they obtained satisfactory results which are close to experimental results.

Many studies on microchannel heat sinks are available in open literature with water and few with nanofluids. However, there is indecisive findings remain especially when comparing with experimental results. So, it is clearly understood that a sound design of micro-channel heat sinks needs a basic understanding of the fluid flow and heat transfer characteristics. Hence, in the present work a detailed study is carried out to analyse the fluid flow and heat transfer characteristics of rectangular micro channel. The observations from water based heat sink are extended to nanofluid based heat sinks to propose a suitable modelling technique for nanofluid flow through conventional microchannels.

The domain of interest is only on single phase flows since numerical modelling of two-phase flow through microchannels involving liquid and vapour is out of the scope. However, when nanofluids are considered for numerical simulation, it is modelled as a two-phase mixture where the base fluid is considered as the primary phase and the suspended nanoparticles as the secondary phase. The improvements and limitations of using nanofluids in microchannel heat sinks are discussed later in this report based on the observations and comparison of results from numerical simulation of both water and nanofluid based heat sinks.

II. CFD ANALYSIS

2.1. Geometry

Microchannel heat sink of channel width 300 μm and 500 μm is considered in the present study. These channels are made of copper and having same foot print area of 25mm × 25mm. The geometrical details are provided in table 2.1. Simulations are carried out on a single channel. Figure 2.1 depicts the micro channel having width 500 μm. The single channel in computational domain consists of fluid flow path and fins on both side and that is shown in figure 2.2.

Table 2.1: Specification of microchannel heat sinks (500μm)

Name	Dimensions
Material	Copper
Total base area	25mm×25mm
Channel space	500(μm)
Fin width	500(μm)
Channel depth, h	1500(μm)
Aspect ratio, α	3
Number of fin row, n	23

2. 2. Grid Generation

CFD preference meshing is done without considering any advanced size function. Since very fine meshing is required in micro meter range channel width, it is observed that considering any advanced size function reduces the orthogonal quality of mesh and increases the skewness.

The edge sizing tool is used to specify the required element size for corresponding edges in microchannel. Mesh element sizes are determined by doing grid independency test. In 500μm channel, meshing edges by 0.01mm (width) × 0.02 mm (height) ×0.05 mm (streamwise) spacing (100 × 90 × 500 cells).

2. 3. Governing Equations

For single phase approach the governing equations are given as follows.

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

$$\nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla P + \nabla\cdot(\mu\nabla\vec{v}) \quad (2)$$

$$\nabla\cdot(\rho\vec{v}\,Cp\,T) = \nabla\cdot(k\nabla T) \quad (3)$$

$$\nabla\cdot(k\nabla T) = 0 \quad (4)$$

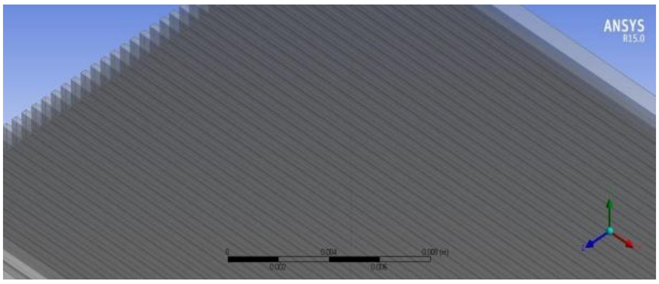

Figure 2.1: Full model of a heat sink

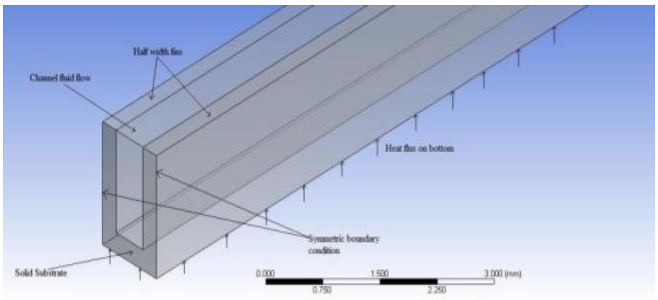

Figure 2.2: Simplified single channel for computation

For nanofluid based microchannel heat sink modelling, the working fluid (nanofluid) is considered to be in two-phase where the primary phase is the base liquid (water) and secondary phase is the solid nanoparticles suspended in the base fluid. The governing equations for the two-phase mixture model are adopted from the work of Esmaeilnejad et.al (Esmaeilnejad, Aminfar, & Neistanak, 2014).

$$\nabla.\left(\rho_m . \vec{v}_m\right) = 0 \quad (5)$$

$$\nabla.\left(\rho_m \vec{v}_m \vec{v}_m\right) = \nabla p_m + \nabla.\left(\tau_m\right) + \nabla.\tau_{Dm} + \rho_m \vec{g} \quad (6)$$

$$\nabla.\left[\left(\varphi\rho_p C_{p,p}\vec{v}_p + (1-\varphi)\rho_f C_{p,f}\vec{v}_f\right)T\right] = \nabla.\left(k_{eff}\nabla T\right) + S_e \quad (7)$$

2. 4. Boundary Conditions

In this present work, two different flow rates are considered, which can be generalised as a high flow rate (711 mL/min) and a low flow rate (311 mL/min). For both the channels, the volume flow rate through the full model domain is maintained constant. For 500 µm and 300 µm channel the heat flux value of 65 W/cm^2 and 100 W/cm^2 are applied on the bottom wall respectively. The top surface of the microchannel is assumed as adiabatic and symmetric boundary condition is given at the side walls of the fin. Also, pressure at the outlet is taken as atmospheric pressure.

III. VALIDATION AND GRID INDEPENDENCE STUDY

A grid independent study is conducted in the present work. The parameter used for conducting the grid independent study is the average Nusselt number. Three different meshes for 500 µm channel are 70 × 60 × 350 cells, 100 × 90 × 500 cells and 130 × 120 × 650 cells. An average Nusselt number obtained for these meshes are 7.90, 7.885 and 7.879 respectively. The average Nusselt number increases by 0.19 % from the first to the second mesh, and only by 0.08 % for further refinement. Hence, the intermediate grid (100 × 90 × 500 cells) is selected for the rest of the simulation. Similarly, grid independence study was done for 300 µm width channel. The simulation results are validated with experimental results [3]. The values of average Nusselt number from the simulation are found in agreement with the experimental results with permissible variations and it is shown in figure 3.1. Hence, it is concluded that the meshing and numerical analysis procedure followed for solving the problem is accurate. The same procedure is used for nanofluid as working fluid.

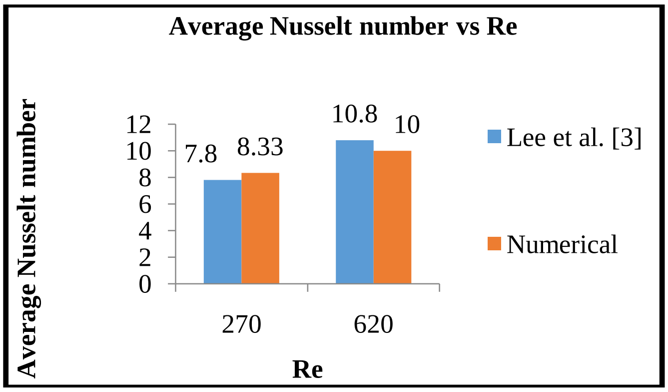

Figure 3.1: Comparison of average Nusselt number for microchannel heat sinks (500 µm channel with water)

IV. RESULT AND DISCUSSION

4. 1. Fluid Flow Characteristics

Figure 4.1 and 4.2 shows the velocity contours of 500 µm rectangular microchannel with water as working fluid at the mid plane of fluid in the longitudinal direction. It can be clearly observed that constant velocity contour is maintained throughout the channel with large velocity gradient from the channel wall to the fluid core. Velocity is zero at convention wall boundary due to no slip boundary condition. It is also observed that parabolic velocity contour is identified along the channel length. Which indicates velocity boundary layer is fully developed and fused at the centre of the channel. Similar velocity profiles are observed in 300 µm microchannel. Since the flow is hydro dynamically developed, there won't be any fluid movement between the fluid layers and hence no proper fluid mixing, which reduces the heat transfer and increase the temperature gradient across the flow. The similar behaviour is observed in 300 µm microchannel also.

The implementation of nanofluids as the working fluid will not have much effect on the fluid flow characteristics because the particle concentrations considered are less than 3 %. Hence water and nanofluids have similar fluid characteristics with the small difference in velocity and pressure drop values. However, nanofluids show significant effect on heat transfer which is discussed in the following section.

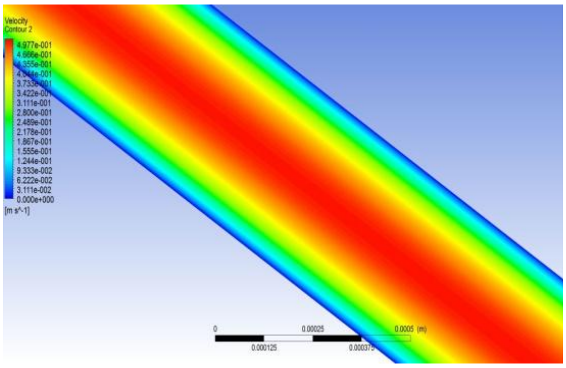

Figure 4.1: Two-Dimensional Velocity contour of flow inside microchannel (500 μm)

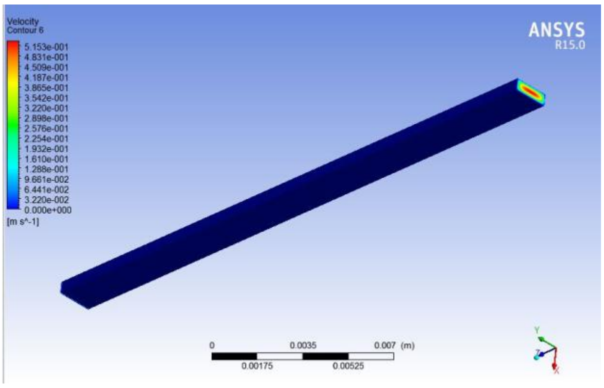

Figure 4.2: Three-Dimensional Velocity contour of flow inside microchannel (500 μm)

4. 2. Heat Transfer Characteristics

Figure 4.3 and 4.4 shows the temperature contour of 500 μm microchannel heat sink. When water is replaced by Al_2O_3 nanofluid of 1 % particle volume concentration, the maximum fin temperature is reduced from 351.75 K to 341.56 K for a flow rate of 13.5 mL/min. This shows a 10 K reduction in temperature which is very remarkable. For a higher flow rate of 30.89 mL/min, nanofluid of 1 % particle volume concentration reduces the temperature by 8 K. By increasing the particle volume concentration to 2 %, the temperature is reduced to 336.23 K for 13.5 mL/min flow rate and 325.85 for 30.89 mL/min flow rate. For 3 % particle volume concentration, these temperatures are 332.88 K and 322.97 K respectively. The Same trend is followed in 300 μm microchannel.

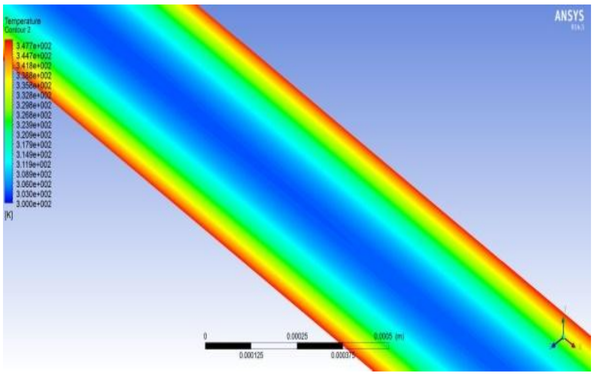

Figure 4.3: Two-Dimensional Temperature contour of flow inside microchannel (500 μm)

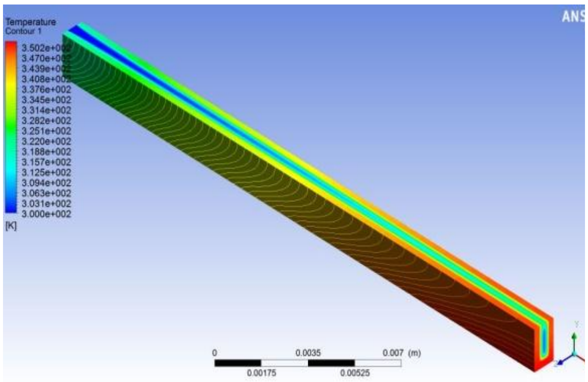

Figure 4.4: Three-Dimensional Temperature contour of flow inside microchannel (500 μm)

Figure 4.5 and 4.6 shows the comparison of the heat transfer coefficient in different channel widths (300 μm and 500 μm) for water and nanofluids by varying particle concentration (1%-3%). Considering the effects of nanofluids in 500 μm conventional channel, replacing water with 1 % Al_2O_3 nanofluid heat transfer coefficient is improved by 20 % for both lower and higher volume flow rates. Further replacing the 1 % Al_2O_3 nanofluid with 2 % Al_2O_3 nanofluid improves the heat transfer coefficient by 12 %. Also a significant improvement is observed with 3 % Al_2O_3 nanofluid. Similarly in 300 μm width channel 1 % Al_2O_3 nanofluid improves heat transfer coefficient by 17% for higher and lower volume flow rates as compared with water. Further replacing the 1 % Al_2O_3 nanofluid with 2 %Al_2O_3nanofluid and 3 %Al_2O_3 nanofluid improves the heat transfer coefficient by 9 -12 % for both the volume flow rates. So, in a generalising trend, nanofluids improve the heat transfer rate considerably compared to the water and increase the heat transfer rate with increasing particle concentration.

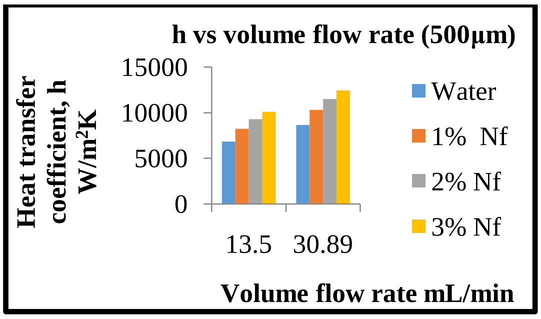

Figure 4.5: Effect of heat transfer coefficient (500µm conventional channel with water and nanofluids)

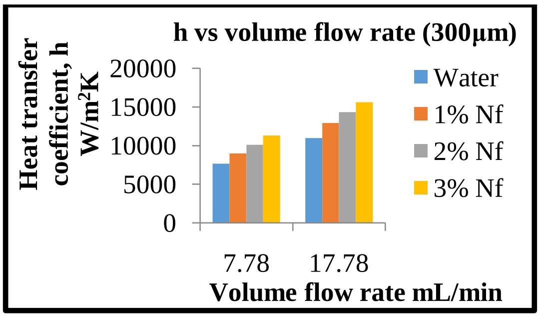

Figure 4.6: Effect of heat transfer coefficient (300µm conventional channel with water and nanofluids)

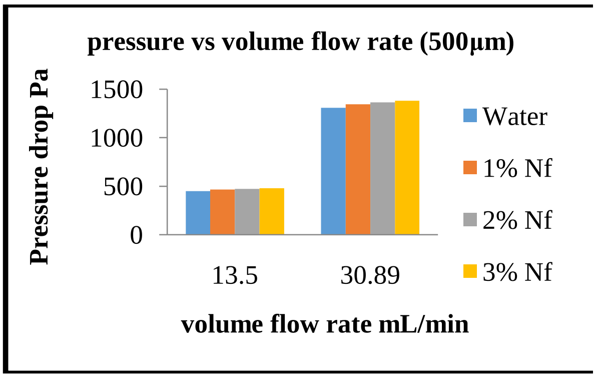

Figure 4.7: Effect of pressure drop (with water and nanofluids)

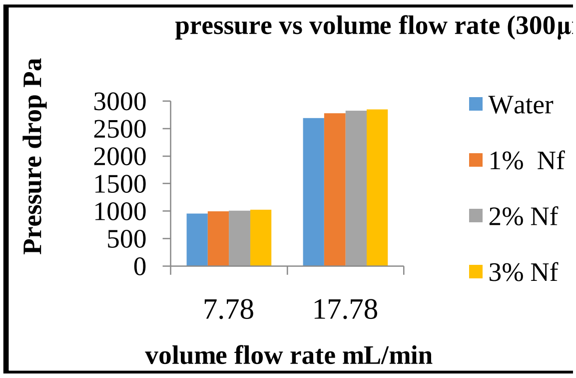

Figure 4.8: Effect of pressure drop (with water and nanofluids)

- Nanofluid indicted as 'Nf'

4. 3. Pressure Drop Characteristics

Figure 4.7 and 4.8 shows the comparison of pressure drop in 500 µm and 300 µm microchannels with both water and nanofluid as working fluid. The pressure values for 500 µm and 300 µm channels with water, at lower volume flow rate are 448.2 Pa and 995.67 Pa respectively. For higher volume flow rate, these values are 1308 Pa and 2689.96 Pa respectively. From the above result it is clearly understand that, 300 µm channel with water as the working fluid, increases pressure drop by 2.9 times the pressure drop in 500 µm channels at lower flow rates (increases pressure drop by 2.7 times pressure drop in 500 µm channels at higher flow rates). This increases the pumping power required for 300 µm channels to be very high than 500 µm channels. Thus the heat transfer enhancement caused by 300 µm channels is compromised by the increased pressure drop which makes 300 µm channel not suitable as an enhancement method.

V. CONCLUSION

Numerical simulation and analysis of water and nanofluid based microchannel heat sink of channel width 500 µm and 300 µm with rectangular finned channels are done and results are analysed. Simulation results of water based heat sinks are validated using existing experimental results. Observations from the detailed analysis of fluid characteristics, heat transfer characteristics and pressure drop characteristics for both water and nanofluid of different particle concentrations helps in understanding the underlying physics of fluid flow and heat transfer phenomenon in a microchannel heat sink. So the conclusions from the present study are stated as follows.

- Water based nanofluid with Al_2O_3 nanoparticles is found to be an excellent working fluid for a microchannel heat sinks. It provides considerable heat transfer enhancement for all the channel widths.
- When nanofluid is used as the working fluid, there is a significant temperature drop in the channel. As results of enhanced thermal conductivity of working fluid.
- Maximum heat flux dissipation is offered by 300 µm channels as observed from the simulation. But the pressure drop values in 300 µm channel is very much higher than the pressure drop in 500 µm channel widths, especially at higher flow rates.
- Usage of nanofluids as working fluids can increase this heat flux dissipation limit by a considerable amount without moving to two-phase heat transfer

Conflict of Interest
We have no conflict of interest and we are not at published same work elsewhere.

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