Heat Transfer Cost-Effectiveness of Nanofluids

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ABSTRACT

When metal or oxide nano particles are dispersed in liquids to form nanofluids, the particles improve thermal conductivity of the liquids. Therefore, it is suggested to use nanofluids as coolants to improve heat-exchanger efficiency. However, the nano particles also cause the increase of fluid viscosity. The present paper has numerically studied the flow and heat transfer of the nanofluids in a 2-D microchannel by using Computational Fluid Dynamics method. It is found that although the nano particles enhance the heat transfer rate of the fluids about certain percentage, the nano particles also cause an increase of viscous shear stress, and further causes an increase of the power consumption to deliver the nanofluids through the microchannels.

Keywords: Nanofluids; Computational fluid dynamics; Micro channels, Heat transfer, Coolants.

1. INTRODUCTION

The nanofluids are produced by dispersing metal or oxide nano particles in liquids. It is found that the metal and oxide nano particles have positive effects to enhance thermal conductivity of the liquids (base liquids). Some small amount of the nano particles dispersed in the base liquids will greatly increase thermal conductivity of the fluids [1-3]. Keblinski *et al.*[1]. proposed some potential mechanisms to explain why the small amount of the nano particles can greatly affect the solution's thermal conductivity.

The nano particles are very stable. They do not settle, and do not clog the components of a flow system, even in a micro fluidic system [1-3].

To explore their advantage, nanofluids are suggested to be used as coolants to improve the thermal efficiency and to reduce the size of heat exchangers. However, the nanofluids also enlarge fluid shear stresses on solid interfaces. This is because that the nano particles increase the viscosity of the fluids. The enlarged shear stresses will increase the fluid drags. This makes it difficult for the nanofluids to flow through the fluidic systems comparing with those base liquids [2, 3]. Therefore, a big pressure difference is required to drive the nanofluids to flow through the fluidic systems. This in turn will cause more power consumption. So, one has to carefully analyze the gain and the loss or cost-effectiveness, before adopting the nanofluids as coolants.

To investigate the cost-effectiveness of using nanofluids as coolants, Computational Fluid Dynamics method is employed to directly simulate the flow and heat transfer of the nanofluids in a 2-dimensional micro channel in the present paper. Basically there are two different numerical methods for doing these. One is based on molecular dynamics which directly focuses on the molecular behaviors of the nano particles. This method needs more *CPU* time and computer memory. The other is based on Navier-Stokes questions with introducing the thermal and dynamic parameters of the nanofluids obtained from the mixture fluid theory and experimental measurements. The latter provides useful information for researchers and engineers to understand the flow and heat transfer profiles of the fluidic devices with less *CPU* time and computer memory [2, 3]. Therefore, it is employed in the present paper to study the cost-effectiveness of the nanofluids in a 2-dimensional micro channel.

2. MATHEMATIC MODEL

In the present study, the nanofluids are regarded as incompressible, well-mixed and uniform single phase solutions. The flows are considered as steady laminar flows. The governing equations are Navier-Stokes and energy equations as below.

$$\nabla \cdot (\rho_{nf} \vec{V}) = 0 \tag{1}$$

$$\nabla \cdot (\rho_{nf} \vec{V}\vec{V}) = -\nabla P + \nabla \cdot (\mu_{nf} \nabla \vec{V}) \tag{2}$$

$$\nabla \cdot (\rho_{nf} \vec{V} Cp_{nf} T) = \nabla \cdot (k_{nf} \nabla T) \tag{3}$$

where ρ_{nf} is nanofluid density, $\vec{V}$ velocity vector, P pressure, μ viscosity, Cp_{nf} nanofluid specific heat capacity, k_{nf} nanofluid thermal conductivity, and T temperature.

The density and specific heat capacity of the nanofluids are calculated using following formulas [2, 3].

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \tag{4}$$

$$Cp_{nf} = (1-\varphi)Cp_{bf} + \varphi Cp_p \tag{5}$$

For viscosity and thermal conductivity, the most widely acceptable data are from experiment measurements. For example, the viscosity and the thermal conductivity of water-γAl_2O_3 solutions are [2, 3].

$$\mu_{nf} = \mu_{bf}(123\varphi^2 + 7.3\varphi + 1) \tag{6}$$

$$k_{nf} = k_{bf}(4.97\varphi^2 + 2.72\varphi + 1) \tag{7}$$

where the subscripts p, bf and nf refer to the particles, the base fluid and the nanofluid respectively; φ is volume concentration of the nano particles. Eq.(4) and Eq.(5) are used for classic mixtures [4]. Eq.(6) is directly adopted from [5], which used a least-squares curve fitting from experimental data. The thermal conductivity expressed in Eq.(7) is from Hamilton and Crosser model [6]. Eq.(4) to Eq.(7) have been successfully employed in [2] and [3]. For ethylene glycol-γAl_2O_3 solutions, similar with Eq.(6) and Eq.(7), the viscosity and thermal conductivity are [2]

$$\mu_{nf} = \mu_{bf}(306\varphi^2 - 0.19\varphi + 1) \tag{8}$$

$$k_{nf} = k_{bf}(28.905\varphi^2 + 2.8273\varphi + 1) \tag{9}$$

There are also some models on viscosity from theoretical analysis. However, these models are less accurate. Here, some recommended models are given below [7]:

Eistein model

$$\mu_{nf} = \mu_{bf}(1 + 1.25\varphi) \tag{10}$$

Brinkman model

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\varphi)^{2.5}} \tag{11}$$

Hamilton and Crosser proposed a model to present colloidal suspensions [6].

$$k_{nf} = k_{bf}\frac{\gamma + (n-1) - (n-1)\varphi(1-\gamma)}{\gamma + (n-1) + \varphi(1-\gamma)} \tag{12}$$

where $\gamma = \dfrac{k_p}{k_{bf}}$, and n is the shape factor respectively. For spherical particles, n has a value of 3.

Bruggeman model [8]

$$k_{nf} = k_{bf}\frac{(3\varphi-1)\gamma + \{3(1-\varphi)-1\} + \sqrt{\Delta_B}}{4} \tag{13}$$

$$\Delta_B = [(3\varphi-1)\gamma + \{3(1-\varphi)-1\}]^2 + 8\gamma \tag{14}$$

3 RESULTS AND DISCUSSIONS

A 2-dimensional microchannel with its width of 200 μm and length of 200 mm (length vs. width ratio is 1000) is employed in the present study.

After grid-independent verifications, it is found that a 11×1001 grid system can provide numerical results with enough accuracy. Therefore this grid system is used for the further calculations. Fig.1 shows the part of the grid system.

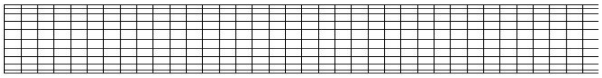

Figure 1: Grid system of the 2-dimensional microchannel, 11×1001

For all numerical simulations, the temperature at the walls is set to be 353K, the temperature of fluid at inlet is fixed to be 293K, and the inlet velocity is given according to Reynolds number based on the microchannel width and water properties. Three different fluids are simulated: pure water, water + 5% Al_2O_3 particles, and water + 10% Al_2O_3 particles. The thermal properties of the nanofluids are considered by introducing Eq.(4) to Eq.(7) into the calculations. The control volume numerical method is used, and numerical iteration is performed till the maximum numerical residual is less than 10^{-7}.

Fig.2 shows the velocity distribution of nanofluid (water + 5% Al_2O_3 particles) at inlet section with Re=10, and Fig.3 gives its temperature distribution.

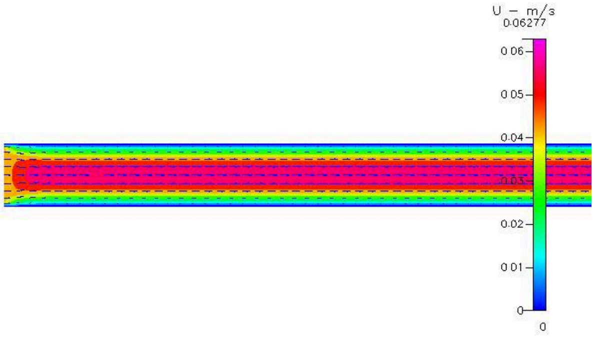

Figure 2: Velocity distribution of nanofluid (water + 5% Al_2O_3 particles) at Re=10

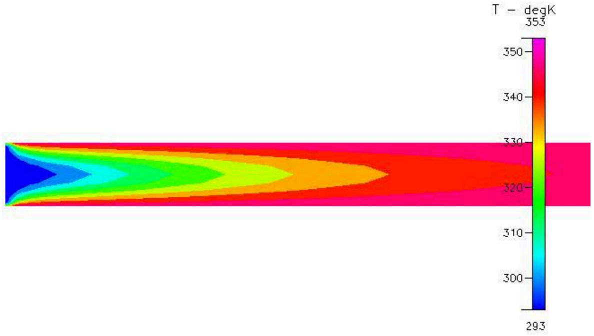

Figure 3: Temperature distribution of nanofluid (water + 5% Al_2O_3 particles) at Re=10

Comparing the velocity and the temperature profiles, it can be seen that the temperature of nanofluids soon becomes a uniformed distribution with same temperature as the hot wall. It only takes a very short distance from the inlet to become a uniform distribution.

The heat transfer rate and drag force are obtained from the computational results. Fig.4 presents the heat transfer ratio of the nanofluid to the pure water (base fluid).

$$R_q = \frac{q_{nf}}{q_{bf}} \tag{8}$$

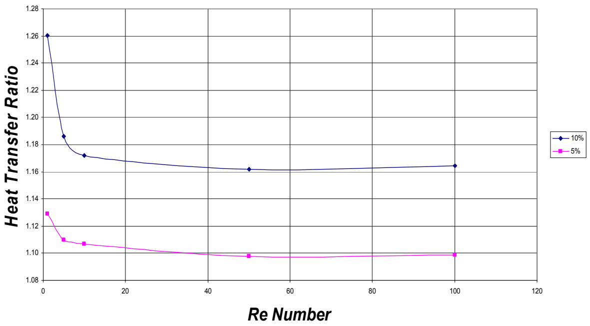

Figure 4: Heat transfer ratio of nanofluid vs. pure water

From Fig.4, it can be seen that the nano particles enhance the heat transferring ability of the base fluid. There is about 10% increase for water + 5% Al_2O_3 particles, while about 16% increase for water + 10% Al_2O_3 particles. After Re>50, the heat transfer ratio is almost a constant.

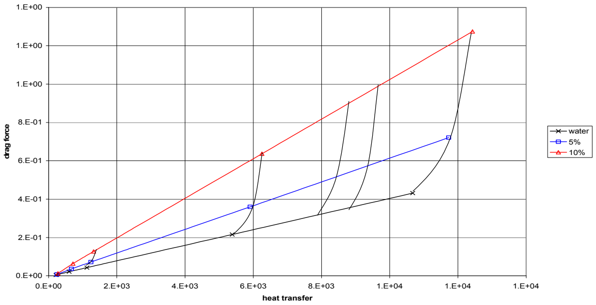

Figure 5: Heat transfer rate vs. drag force of nanofluids

Fig.5 shows the curves of the heat transfer versus the drag force of the microchannel, with various volume concentrations of the nano particles. The horizontal axis is the heat transfer, and the vertical axis presents the drag force. The marks on the curves stand for Reynolds numbers. From left to right, Reynolds numbers are 1, 5, 10, 50, and 100 respectively, which can be regarded as flow rate here. It is clearly shown that at the same flow rate, the heat transfer rate increases with the presence of the nano particles in fluids. The more nano particles, the more increase of the heat transfer rate. However, it also can be seen that there is an increase of the drag force. The increase of the drag force is very significant with the increase of the volume concentration of the nano particles.

As we know that the drag force is directly linked with the power consumption. In order to drive nanofluids through microchannels, the power has to be consumed to overcome the drag force. The large drag force means that more power is required to pump the nanofluids, or in other words, a more powerful pump is required for the purpose of delivering nanofluids.

If examining Fig.5 carefully, one can find that at same flow rate the increase of the drag force is much faster than the increase of heat transfer. For the same amount of heat transfer, the nanofluids will consume more power than the water does. In other words, if one uses the water as the coolant, one can achieve same heat transfer target by simply increasing the flow rate of the water. As a result, one can use less power by using the water comparing with by using the nanofluids. Here, it should be emphasized that the manufacturing cost of the nano particles and the nano fluids have not been included.

As shown in Fig.3, the temperature of the incoming cold nanofluids soon increases to the hot wall temperature, and becomes a uniform distribution. This means at the end of the channel, the outgoing fluids will be of the same temperature of the hot wall. Therefore, the factors which determine the heat flux out of the channel are specific heat capacity and fluid flow rate, not the thermal conductivity and the heat transfer rate of the nanofluids. So, in our present case, as the outgoing fluids have the same temperature of the hot wall, we need only to see fluids' specific heat capacity. Now we turn to discuss Eq.(4) and Eq.(5). We rewrite Eq.(5) by dividing Cp_{bf} both sides of Eq.(5).

$$\frac{Cp_{nf}}{Cp_{bf}} = 1 + \varphi(\frac{Cp_p}{Cp_{bf}} - 1) \tag{9}$$

where Cp_{nf} / Cp_{bf} is the ratio of specific heat capacity of nanofluids to that of base fluid, and Cp_p / Cp_{bf} is the ratio of specific heat capacity of nano particles to that of base fluid. As we know, the base liquid (the water at the present case) usually has much higher specific heat capacity than those of solid metals. Therefore, Cp_p / Cp_{bf} is less than 1. So, from the right hand side of Eq.(9), we can conclude $Cp_{nf} / Cp_{bf} < 1$ for water base nanofluids. This implies that the nano particles improve heat transfer rate of nanofluids, but decrease the specific heat capacity of nanofluids.

For a channel or a tube used for heat exchanger, the liquid coolants will reach temperature of hot wall at certain length from the inlet section. Because of enhanced heat transfer rate, nanofluids will reduce this length comparing pure water. If the channel or tube has a length longer than the length, the nanofluids will have no effect to improve efficiency of a heat exchanger.

4. CONCLUSIONS

Flow and heat transfer of nanofluids in a 2-dimensional microchannel are numerically studied in the present paper using CFD method through introducing the thermal and dynamic parameters of the nanofluids. It is found that:

- Nano particles in fluids enhance heat transfer rate of fluids and increase viscosity as well.
- Increase of heat transfer rate is less significant than increase of viscous drag.
- Nanofluids have lower specific heat capacity than pure water.
- For long channel or tube, nanofluids will have no improvement for heat exchanging.
- Using the pure water as coolant will be more cost-effective in the present model.

REFERENCES

[1]. P. Keblimski, et al, "Mechanisms of Heat Flow in Suspensions of Nano-sized Particles (Nanofluids)", *International Journal of Heat and Mass Transfer,* 45 (2002) 855-863.

[2]. S.E.B. Maiga, et al, "Heat Transfer Behaviours of Nanofluids in a Uniformly Heated Tube", *Superlattices and Microstructures*, 35 (2004) 543-557.

[3]. G. Roy, C.T. Nguyen, and P.R. Lajoie, "Numerical Investigation of Laminar Flow and Heat Transfer in a Radial Flow Cooling System with the Use of Nanofluids", *Superlattices and Microstructures*, 35 (2004) 497-511.

[4]. B.C. Pak, Y.I. Cho, "Hydrodynamic and heat transfer study of dispersed fluids with Submicro metal oxide particles", *Exp. Heat Transfer* 11 (2) (1998) 151-170

[5]. X. Wang, X. Xu, and S.U.S. Choi, "Thermal Conductivity of Nanoparticles – fluid mixture", *J. Thermophys, Heat Transfer* 13 (4) (1999) 474 - 480

[6]. R.L. Hamilton, O.K. Crosser, "Thermal Conductivity of Heterogeneous Two-components System", *I & EC Fundamentals* 1 (3) (1962) 187-191

[7]. Y. Xuan and W. Roetzel, "Conceptions for heat transfer correction of nanofluids", Int. J. Heat Mass Transfer 43, 3701 (2000)

[8]. B.X. Wang, L.R. Zhou, and X.F. Peng, "A fractal model for predicting the effective thermal conductivity of liquid with suspension of nanoparticles", Int. J. Heat Mass Transfer 46, 2665 (2003)