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PARTICLE EFFECTS ON CONVECTIVE HEAT TRANSFER OF NANOFLUIDS IN A MICROTUBE

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ABSTRACT Literature searches revealed no studies that systematically examine how particles affect microscale convective heat transfer of nanofluids. This paper presents a numerical study on the particle effects on forced convection of nanofluids through a microtube. A thermal-flow model is firstly built and solved by using the marching implicit (MI) procedure. The computational results reveal that the particle concentration and interaction effects are to increase the pressure drop (or reduce the volume flow rate); moreover, for a fixed volume flow rate, the effects are to enhance the heat transfer. The role of particle interaction becomes more significant when the particle concentration increases and could be found to result in an increase in convective heat transfer.

INTRODUCTION

Nanofluid is a suspension of nanoparticles in a base fluid. In this type of fluid, the van der Waals force energy, thermal motion energy, and magnetic interaction energy between particles may cause all kinds of new magnetic, electrical, thermal, and mechanical behavior. Nowadays nanofluid is widely used in such systems as heat exchangers, loud speakers, actuators, bearings, density separation, tagged particle separation, inkjet printers, spin coating, dampers, thermal healing, targeted drug delivery, and many others. However, despite the wide use of magnetic nanofluids, basic scientific research with respect to heat transfer is quite sparse.

Jang and Choi [2006] numerically investigated the cooling performance of a microchannel heat sink with water-based copper and carbon nanofluids. Jung *et al.* [2009] developed to measure the convective heat transfer coefficient for water-based and water/ethylene glycol-based Al_2O_3 nanofluids in rectangular microchannels. Mohammed *et al.* [2010] attempted to simulate the heat transfer of a water-based Al_2O_3 nanofluid inside microchannel heat sinks. Niu *et al.* [2012] predicted the convective heat transfer of non-Newtonian nanofluids in a microtube. Salman *et al.* [2012] utilized a numerical method to investigate the convective heat transfer of nanofluids with different types of nanoparticles in microtubes. conducts an analysis of convective heat transfer of magnetic nanofluids in an isothermally heated microtube. Luo and Weng [2015] numerically and experimental investigated the effects of particle volume fraction and external magnetic field strength on the convective heat transfer of water-based Fe_3O_4 nanofluids in microtubes. Recently, Weng and Huang [2015] presented a numerical and experimental study on the interaction effect of particles on nanofluid flow through microtubes of radii 140 and 231 μm.

The present focus is being made on convective heat transfer due to water-cooling issues at the micro/nanoscale. Until recently however, there were no studies that have examined how particles affects microscale convective heat transfer of nanofluids. In this study, the influence of particles on forced convection of nanofluids in a microtube is investigated numerically. The detailed numerical procedure is described. The particle effects for different particle concentrations and interaction strengths are then discussed. The results can be used as a reference for any future studies on micro/nanoscale thermal-fluid transport phenomena.

METHODOLOGY

Consider a horizontal isothermally heated microtube of length l and radius r_w. The flow originates from a reservoir in a reference state and terminates in a discharge area of lower pressure. Let Z and R denote the dimensionless cylindrical coordinates, let U and V denote the components of velocity in Z and R directions, and let Θ denote the dimensionless temperature. The difference governing equations described by the boundary-layer continuity, momentum, and energy equations for two-dimensional steady flow of an incompressible fluid with negligible viscous dissipation are

$$\frac{V_{i,j}-V_{i,j-1}}{\Delta R}+\frac{V_{i,j}}{R_{i,j}}+\frac{(U_{i,j}-U_{i-1,j})+(U_{i,j-1}-U_{i-1,j-1})}{2\Delta Z}=0 \tag{1}$$

$$\begin{aligned} M_\rho V_{i-1,j}\frac{U_{i,j+1}-U_{i,j-1}}{2\Delta R}+M_\rho U_{i-1,j}\frac{U_{i,j}-U_{i-1,j}}{\Delta Z} \\ =-\frac{P_i-P_{i-1}}{\Delta Z}+M_\mu\frac{U_{i,j+1}-2U_{i,j}+U_{i,j-1}}{(\Delta R)^2}+M_\mu\frac{1}{R_{i,j}}\frac{U_{i,j+1}-U_{i,j-1}}{2\Delta R}\end{aligned} \tag{2}$$

$$M_\rho M_c\left(V_{i-1,j}\frac{\Theta_{i,j+1}-\Theta_{i,j-1}}{2\Delta R}+U_{i-1,j}\frac{\Theta_{i,j}-\Theta_{i-1,j}}{\Delta Z}\right)=\frac{M_k}{\Pr}\left(\frac{\Theta_{i,j+1}-2\Theta_{i,j}+\Theta_{i,j-1}}{(\Delta R)^2}+\frac{1}{R_{i,j}}\frac{\Theta_{i,j+1}-\Theta_{i,j-1}}{2\Delta R}\right) \tag{3}$$

where the subscript Δ represents the grid spacing, *i* and *j* represent the grid locations in the Z and R directions, respectively, $i=2,3,4\ldots$ and $j=2,3,4,\ldots,M$, Pr is the Prandtl number, and

$$M_\rho=\frac{\rho_r}{\rho_{r,f}},\quad M_\mu=\frac{\mu_r}{\mu_{r,f}},\quad M_c=\frac{c_r}{c_{r,f}},\quad M_k=\frac{k_r}{k_{r,f}} \tag{4}$$

In the equation, the subscript r represents the reference value at a particular temperature, and the density, the viscosity, the constant-pressure specific heat, and thermal conductivity are, respectively,

$$\left.\begin{aligned} &\rho_r=\rho_{r,s}\varphi_s+\rho_{r,a}(\varphi-\varphi_s)+\rho_{r,f}(1-\varphi)\\ &\mu_r=\mu_{r,f}(1-\varphi)^{-5\varepsilon/2}\\ &c_r=\frac{\rho_{r,s}c_{r,s}\varphi_s+\rho_{r,a}c_{r,a}(\varphi-\varphi_s)+\rho_{r,f}c_{r,f}(1-\varphi)}{\rho_r}\\ &k_r=k_{r,f}\left(1-\frac{3(k_{r,f}-k_{r,a})(\varphi-\varphi_s)}{2k_{r,f}+k_{r,a}+(\varphi-\varphi_s)(k_{r,f}-k_{r,a})}-\frac{3(k_{r,f}-k_{r,s})\varphi_s}{2k_{r,f}+k_{r,s}+\varphi_s(k_{r,f}-k_{r,s})}\right)\end{aligned}\right\} \tag{5}$$

Here the subscript *f* represents the carrier liquid value, φ is the particle volume fraction, ε is the viscosity correction factor characterizing the particle interaction effect. It should be noted from Figure 1 that ε is a nonlinear function of φ ($\varepsilon=f(\varphi)$).

The corresponding difference boundary conditions are as follows:

for $i=1$ *and* $2\le j\le M$:

$$U_{1j}=1,\quad V_{1j}=0,\quad \Theta_{1j}=0,\quad P_{1j}=\Delta P-\frac{1}{2}M_\rho \tag{6}$$

for $i=N+1$ *and* $2\le j\le M$:

$$P_{N+1,j} = 0 \quad (7)$$

for $j = 1$ *and* $2 \le i \le N$:

$$U_{i,1} = U_{i,2},\ V_{i,1} = V_{i,2},\ \Theta_{i,1} = \Theta_{i,2} \quad (8)$$

for $j = M + 1$ *and* $2 \le i \le N$:

$$U_{i,M+1} = 0,\ V_{i,M+1} = 0,\ \Theta_{i,M+1} = 1 \quad (9)$$

The difference flow rate conservation equation is

$$1 - 2\left(U_{i,1} R_{i,1} \Delta R/2 + U_{i,2} R_{i,2} \Delta R + U_{i,3} R_{i,3} \Delta R + \ldots + U_{i,M} R_{i,M} \Delta R + U_{i,M+1} R_{i,M+1} \Delta R/2\right) = 0 \ . \quad (10)$$

The numerical method used for this study is the marching implicit procedure (MI). To obtain the numerical solutions for the abovementioned convective heat transfer problem, the following procedure must be satisfied.

1. Fix the values of ρ_r, μ_r, c_r and k_r .
2. Presume the tube length to be L_g .
3. Set the pressure drop to ΔP
4. Enter the inlet conditions at $i = 1$.
5. Set the loop iteration to $i = 2$.
6. Conduct the numerical iteration procedure to find $U_{2,j}$, $V_{2,j}$, P_{2j} and Θ_{2j} .
7. Set up $i = i + 1$ and conduct the numerical iteration procedure to find $U_{i,j}$, $V_{i,j}$, P_{ij} and Θ_{ij} .
8. The program then stop and the actual tube length L is estimated when the outlet conditions are satisfied.

In this procedure, the tri-diagonal matrix algorithm (TDMA) method is used to solve the momentum equation (2) and the energy equation (3) so as to find $U_{i,j}$ and Θ_{ij} . The continuity equation (1) is used to find $V_{i,j}$. The secant method is used to solve the flow rate conservation equation (10) so as to find P_{ij} . The grid numbers for Z and R directions are 1000 and 400, respectively. As a convergence test, a grid analysis has been performed for such uniform meshes.

FINDINGS

In our investigation of the effects of particles on the thermal flow fields and the corresponding characteristics of nanofluids in an isothermally heated microtube, we employed the marching implicit (MI) procedure to obtain simulation results. The chosen reference value of Pr for the analysis is 6.2073, and the parametric analysis is performed over the ranges $0 \le L \le 20$, $0 \le \varphi \le 3.2\%$ and $0 \le \xi \le 6$.

The interaction between the particles in a nanofluid and the wall of the microtube increases with the particle volume fraction. The higher the particle volume fraction, the greater the effects of particle-particle and particle-wall interaction (the more significant the ΔP rise with L). It is found from figures unshown that, for the thermal-flow fields, the particle interaction causes a velocity decrease near the wall, a velocity increase close to the axis of the microtube, and a temperature increase in the whole microtube. As for the thermal-flow characteristics, the greater the particle volume fraction, the more significant is the increase of the flow drag. For a fixed flow rate, one can find that the effects of particles become more significant when the particle volume fraction increases and that it could result in an increase in convective heat transfer.

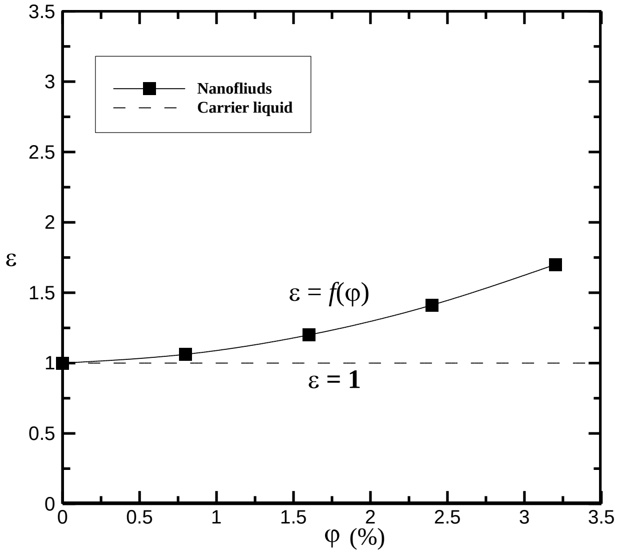

Figure 1. Viscosity correction factor ε versus particle volume fraction φ for nanofluid flow through microtubes of radius 231 μm .

CONCLUSIONS

This paper has conducted a numerical study on the influence of particles on forced convection of nanofluids in a microtube. The developing-flow simulation is implemented by using a marching implicit (MI) procedure. Results showed that, when the particle concentration and interaction increases, the pressure drop increases (or the volume flow rate decreases). Moreover, for a fixed volume flow rate, the particle concentration and interaction effects are to enhance the convective heat transfer.

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