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Numerical study of hydrodynamic and heat transfer of nanofluid flow in microchannels containing micromixer ☆

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ABSTRACT

In this study heat transfer and fluid flow of Al_2O_3/water nanofluid in two dimensional parallel plate microchannel without and with micromixers have been investigated for nanoparticle volume fractions of $\phi=0, \phi=4\%$ and base fluid Reynolds numbers of $Re_f=5$, 20, 50. One baffle on the bottom wall and another on the top wall work as a micromixer and heat transfer enhancement device. A single-phase finite difference FORTRAN code using Projection method has been written to solve governing equations with constant wall temperature boundary condition. The effect of various parameters such as nanoparticle volume fraction, base fluid Reynolds number, baffle distance, height and order of arrangement have been studied. Results showed that the presence of baffles and also increasing the Re number and nanoparticle volume fraction increase the local and averaged heat transfer and friction coefficients. Also, the effect of nanoparticle volume fraction on heat transfer coefficient is more than the friction coefficient in most of the cases. It was found that the main mechanism of enhancing heat transfer or mixing is the recirculation zones that are created behind the baffles. The size of these zones increases with Reynolds number and baffle height. The fluid pushing toward the wall by the opposed wall baffle and reattaching of separated flow are the locations of local maximum heat transfer and friction coefficients.

1. Introduction

Convective heat transfer in a microchannel is a very effective method for the thermal control micro electronic device because of the high surface area to volume ratio of these channels. So, the ability to remove heat from the high rate flux region becomes an important factor in designing microsystems. Gamrat et al. [1] numerically investigated the thermal entrance effect and conduction/convection coupling effects in both three dimensional and two dimensional microchannels. Zhang et al. [2] numerically analyzed the effect of roughness element with different shapes, like triangular, rectangular and semicircular on the thermal and hydrodynamic characteristics. Their results showed improved performance of heat transfer by roughness. Del Guidice et al. [3] numerically investigated the effect of viscous dissipation and temperature dependant viscosity in developing flow of fluids in straight microchannels with different cross sections and found out that these effects cannot be neglected in a wide range of operative conditions.

Another approach to enhance the heat transfer in the microchannels may be utilizing nanofluids as working fluids. This can be possible because nanofluids exhibit unusual thermal and fluid properties, which in conjunction with microchannel systems may provide enhanced heat transfer performances. Yeul Juang et al. [4] experimentally investigated the convective heat transfer and friction factor of Al_2O_3/water nanofluid with various particle volume fractions in rectangular microchannels. They observed an increase in heat transfer coefficient with increase in volume fraction and Reynolds number. Akbarinia et al. [5] numerically investigated the forced convection slip and none slip nanofluid flow in two dimensional microchannels to study the effect of nanoparticle volume fraction in heat transfer enhancement. They have reported that with stabilizing the nanofluid Reynolds number, major enhancement on the Nusselt number is not due to nanoparticle concentration. Ahmed et al. [6] investigated the heat transfer enhancement and pressure drop of the copper–water nanofluid through isothermally heated corrugated channel. In their study the Reynolds number and nanoparticle volume fraction are ranged from 100 to 1000 and from 0% to 5% respectively. The results demonstrated that the local Nusselt number is higher in the converging section than in the diverging section along the wall. Tahir and Mital [7] numerically investigated the developing laminar forced convection flow of Al_2O_3/water nanofluid in a circular tube under uniform heat flux. They studied the effect of Reynolds number, volume fraction of nanoparticles and particle diameter by using discrete phase modeling (DPM).

A very different application of nanofluids could be in modern medicine, where for example nanodrugs are mixed in microchannels for controlled delivery with bio-MEMS [8]. In such applications (for example, biological processing, lab on the chips, micro-reactors and fuel cells)

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Nomenclature

C_p	specific heat (J kg^{-1} K^{-1})
d	nanoparticle diameter (m)
k	thermal conductivity (W m^{-1} K^{-1})
Nu_P	peripheral-averaged Nusselt number of microchannel cross section
Nu	Nusselt number $= \frac{hL}{k_f} = \frac{q_w L}{(T_w - T_b) k_f}$
$\overline{Nu}$	averaged Nusselt number $= \frac{1}{S}\int_0^S Nu_P dx$
p	pressure (Pa)
Po	Poiseuille number (f Re_f)
Po_P	peripheral-averaged of Poiseuille number of microchannel cross section
Po*	non-dimensional wall shear stress $= \frac{2\tau_w}{\rho_f u_{in}^2} \times Re_f$
$\overline{Po}$	average Poiseuille number $= \frac{1}{S}\int_0^S Po_P dx$
q	heat flux
Re_f	fluid Reynolds number $= \frac{\rho u_{in} L}{\mu}$
Re_{nf}	nanofluid Reynolds number $= \frac{\rho_{nf} u_{in} L}{\mu_{nf}}$
T	temperature (K)
u	velocity in the streamwise direction (m s^{-1})
v	velocity in the normal direction (m s^{-1})
x	coordinate in the streamwise direction (m)
y	coordinate in the normal direction (m)

Greek letters

ϕ	nanoparticle volume fraction
μ	dynamic viscosity (N s m^{-2})
ρ	density (kg m^{-3})

Subscripts

B	bottom wall
f	fluid
in	inlet condition
nf	nanofluid
p	solid nanoparticles
T	top wall
w	the wall

rapid and complete mixing of fluid is required. Microchannel flows, due to very low flow rate, are characterized by very low Reynolds number. Owing to the predominantly laminar flow, it is difficult to achieve effective mixing fluids. If the mixing is obtained primarily by a diffusion mechanism then fast mixing becomes impossible. Hence microfluidic mixing is a very challenging problem because it requires fast and efficient mixing of low diffusivity fluids [9]. In general, micromixers are classified into two types: active and passive. In order to achieve rapid mixing in passive micromixers, obstacle structures were inserted into microchannels to enhance the advection effect via splitting, stretching, breaking and folding of liquid flows. Afrooz Alam and Kim [10] numerically investigated the mixing of fluids in a microchannel with grooves in its side walls and found out that it has better mixing performance than smooth channel at Re > 10. Chung et al. [11] designed, fabricated and simulated a passive micromixer which contains some baffles with different arrangement.

In the present study the effect of baffled micromixer on the flow structure and heat transfer of single phase nanofluid in microchannel has been investigated. The effect of various geometrical and flow parameters such as height and different arrangement of baffles, Reynolds number and nanoparticle volume fraction, etc. have been studied.

2. Geometrical configuration

The geometrical configuration of the considered problem has been shown in Fig. 1. The microchannel consists of two parallel plates with the distance of L and the length of S. Two baffles with the heights of e1 and e2 are placed inside the channel. The distances of the first and second baffles from the beginning of the channel are sb1 and sb2, respectively. The baffles are assumed adiabatic with zero thickness in the numerical simulation. The steady, laminar flow of nanofluid, enters the constant wall microchannel with hydrodynamically fully developed velocity and uniform temperature.

3. Governing equations and boundary conditions

Under the assumptions of ultra-fine particles (<100 nm) and no slip velocity between the discontinuous phase of the nanoparticles and the continuous liquid and the local thermal equilibrium between them, particle–liquid mixture may be considered as a conventional single-phase pure fluid [11,12]. Also, physical properties of the nanofluid are assumed constant and are evaluated at the reference state corresponding to the fluid inlet temperature. Under the above conditions, the corresponding non-dimensional governing equations are written as follows:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re_f}\frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu_f}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re_f}\frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu_f}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) \tag{3}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{Re_f Pr_f}\frac{\left(\rho C_p\right)_f}{\left(\rho C_p\right)_{nf}}\frac{k_{nf}}{k_f}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right). \tag{4}$$

The non-dimensional parameters used in the above equations have been defined as follows:

$$X = \frac{x}{L}, Y = \frac{y}{L}, U = \frac{u}{u_{in}}, V = \frac{v}{u_{in}}, \theta = \frac{T - T_w}{T_{in} - T_w}, P = \frac{p}{\rho_f u_{in}^2}$$
$$Re_f = \frac{\rho_f u_{in} L}{\mu_f}, Pr_f = \frac{\mu_f C_{pf}}{k_f}. \tag{5}$$

The used boundary conditions to solve the Eqs. (1) to (4) have been given in Fig. 1.

4. Physical properties of the nanofluids

The nanofluid in this study is composed of water and 36 nm particles of Al_2O_3. The physical properties of the nanofluid in the above equations can be obtained as follows.

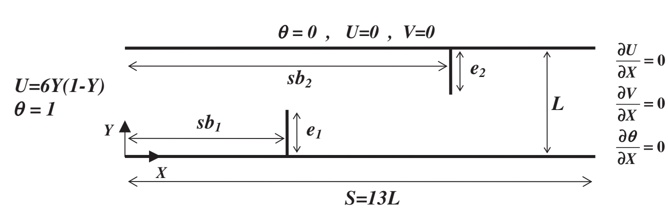

Fig. 1. Geometrical configuration and boundary conditions.