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An investigation on the hydrodynamic and heat transfer of nanofluid flow, with non-Newtonian base fluid, in micromixers

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ABSTRACT

In this study heat transfer and fluid flow of a non-Newtonian nanofluid in two dimensional parallel plate microchannel without and with micromixers have been investigated for nanoparticle volume fractions of $\phi = 0, \phi = 0.04$ and nanofluid Reynolds numbers of $Re_{nf} = 5$, 20, 50. The nanofluid is composed of CuO nanoparticles and the non-Newtonian base fluid of 0.5 wt% aqueous solution of Carboxymethyl Cellulose (CMC). Two baffles on the bottom and top walls work as micromixer. A single-phase finite difference FORTRAN code using Projection method has been written to solve the governing equations with constant wall temperature boundary condition. A new correlation for thermal conductivity of this nanofluid has been introduced and also the effect of various parameters such as the baffles distance, height and order of arranging has been studied. Results show that the presence of baffles and also increasing the Re number and nanoparticle volume fraction increases the local and average heat transfer and friction coefficients of non-Newtonian nanofluid. Also, the effect of nanoparticle volume fraction on heat transfer coefficient is more than 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 Re 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 microchannels is a very effective method for the thermal control of microelectronic devices because of the high surface area to volume ratio in these channels. So, the ability to remove heat from the high rate flux region becomes an important factor in designing microsystems. Chu et al. [1] conducted an experiment to investigate the behavior of water through curved rectangular microchannels with different aspect ratio and curvature radii for different Reynolds numbers. Valdes et al. [2] numerically investigated the effect of surface roughness in laminar fluid flow through annular microchannels. Rahimi and Mehryar [3] studied the wall thermal conductivity and thickness on local Nusselt number at entrance and ending region of circular cross sectional microchannels. Del Guidice et al. [4] investigated the effect of viscous dissipation and temperature dependant viscosity in developing flow of fluids in straight microchannels with different cross sections numerically 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. Li and Kleinstreuer [5] studied the thermal performance of CuO/water nanofluid flow of in a trapezoidal microchannel. The results showed that nanofluids enhance the thermal performance of microchannel mixture flow with a small increase in pumping power. The thermal performance and pressure drop increased with volume fraction.

Wu et al. [6] experimentally investigated the flow and heat transfer characteristics of Al_2O_3/H_2O nanofluids through trapezoidal microchannels. Results showed that the pressure drop and flow friction of the nanofluids increased slightly when compared with that of the pure water, while the Nusselt number increased considerably.

Manca et al. [7] numerically investigated the forced convective Al_2O_3/water nanofluid in a two dimensional ribbed channel in turbulent regime under constant heat flux. They observed an

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Nomenclature

C_p	specific heat
d	diameter
f	friction coefficient = $\frac{2\tau_w}{\rho \bar{u}_{in}^2}$
k	thermal conductivity
K_B	Boltzman constant $= 1.3807 \times 10^{-23}$
m	consistency coefficient
n	power law index
Nu	Nusselt number $= \frac{hL}{k_{nf}} = \frac{q_w L}{(T_{w-} T_b) k_{nf}}$
$\overline{\mathrm{Nu}}$	average Nusselt number $= \frac{1}{S} \int_0^S \mathrm{Nu}_P dx$
Nu_P	peripheral-averaged Nusselt number of microchannel cross section
P	non-dimensional pressure
Po	Poiseuille number = $f\mathrm{Re}_{nf}$
$\overline{\mathrm{Po}}$	average Poiseuille number = $\frac{1}{S} \int_0^S \mathrm{Po}_P dx$
Po_P	peripheral-averaged of Poiseuille number of microchannel cross section
Po^*	non-dimensional wall shear stress = $\frac{2\tau_w}{\rho_{nf} \bar{u}_{in}^2} \mathrm{Re}_{nf}$
Pr	Prandtle number
q	heat flux
Re	Reynolds number
T	temperature
u	velocity in x direction
$\bar{u}$	average velocity
U	non-dimensional velocity in x direction
v	velocity in y direction
V	non-dimensional velocity in y direction
$\vec{\mathbf{V}}$	velocity vector
x	coordinate in the streamwise direction
X	non-dimensional coordinate in the streamwise direction
y	coordinate in the normal direction
Y	non-dimensional coordinate in the normal direction

Greek letters

ϕ	nanoparticles volume fraction
μ	dynamic viscosity
ρ	density
$\bar{\bar{\tau}}$	shear stress tensor
$\bar{\bar{\dot{\gamma}}}$	shear rate tensor

Subscripts

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

Superscript

T	transpose

enhancement in heat transfer with increasing particle volume concentration and Reynolds number. Aswadi et al. [8] numerically investigated the laminar forced convection flow of nanofluids flow over a 2D horizontal backward facing step in a duct. In their study eight different nanoparticles (Au, Ag, Al_2O_3, CuO, Cu, diamond, SiO_2, TiO_2) with volume fraction of 5% are dispersed in a base fluid. Their results show that the nanofluid with low dense nanoparticles such as SiO_2 in comparison with high dense nanoparticles like Au has higher velocity and static pressure and also higher wall shear stress at top and bottom walls.

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 [9]. In such applications (for example, biological processing, lab on the chips, micro-reactors and fuel cells) rapid and complete mixing of fluid is required. Microchannel flows, due to very low flow rate, are characterized by very low Reynolds numbers. 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 [10]. 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. Alam and Kim [11] 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 $Re > 10$. Liu et al. [12] showed that a three dimensional serpentine microchannel with a “C-shaped” repeating units, as a means of implementing chaotic advection, enhance the fluid mixing in comparison with a square-wave channel for different Re numbers.

In most cases, the nanoparticles are added to a Newtonian base fluid like water, oil and ethylene glycol. There are only a few experimental studies on the nanofluids with non-Newtonian base fluids. For example Hojjat et al. [13,14] experimentally investigated the forced convective heat transfer of non-Newtonian nanofluid flow in a uniformly heated horizontal tube under laminar and turbulent regime. In their study nanofluids are made by dispersion of γ Al_2O_3, CuO, and TiO_2 nanoparticles in an aqueous solution of 0.5 wt% of Carboxymethyl Cellulose (CMC). Their results show that both average and local heat transfer coefficients of nanofluids are larger than the base fluid. Also, with augmentation of nanoparticle concentration the enhancement of heat transfer coefficient increases. These researchers in another study measured the thermal conductivity of the base fluid and these non-Newtonian nanofluids with various nanoparticle volume concentrations at different temperatures [15]. Results show that the thermal conductivity of nanofluids is higher than the base fluid. Also, the thermal conductivity of these nanofluids increases with the temperature. Rheological behavior of these non-Newtonian nanofluids has been studied in Ref. [16]. The results show that the above base fluid and nanofluids are pseudoplastic or shear thinning. Yang et al. [17] experimentally compared the thermal conductivity and viscosity of viscoelastic-fluid-based (aqueous solution of cetyltrimethylammonium chloride/sodium salicylate)/Cu nanofluids and distilled water based nanofluids. The results showed that the viscoelastic-fluid-based Cu nanofluids have a higher thermal conductivity than viscoelastic base fluid. Also the viscoelastic-fluid-based Cu nanofluid shows a non-Newtonian behavior in its viscosity, and the viscosity increases with the increase of Cu nanoparticle concentration. Liu and Liao [18] studied the characteristics of convective heat transfer and flow resistance in turbulent pipe flows of viscoelastic fluid, water-based and viscoelastic-fluid-based nanofluids (VFBN) containing copper (Cu) nanoparticles. Experimental results indicated that the VFBN flows showed better heat transfer properties than viscoelastic base fluid flows and lower flow resistances than water-based nanofluid flows.

The thermal conductivity and shear viscosity of a viscoelastic-fluid-based nanofluid (VFBN) using viscoelastic aqueous solution