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Effects of nanoparticle migration on non-Newtonian nanofluids in a channel with multiple heating and cooling regions

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ABSTRACT

Laminar forced convection nanofluids based non-Newtonian flow in a horizontal parallel channel with multiple regions of heating and cooling are investigated, taking into account the inhomogeneous distribution of nanoparticles. The non-Newtonian behaviour of nanofluids is described by the power-law model. The velocity, temperature and concentration fields, heat transfer coefficient ratio, and pressure drop are obtained numerically by solving the coupled momentum, energy and concentration equations. Results based on assumption of homogeneous and inhomogeneous distribution of nanoparticles are compared with each other. It is found that the detailed information of velocity, temperature and pressure drop obtained by these two opposite assumptions are largely different. The non-uniform distribution of nanoparticles has a much weaker influence on temperatures compared to the uniform distribution; and the non-uniform distribution of nanoparticles in the base fluid results in a smaller pressure drop than the uniform cases do. The above findings highlight the necessity and significance of studying the effects of nanoparticles' sedimentation and precipitation on heat and mass transfer for related industrial applications. And the thermal performance of power-law nanofluids investigated in this paper may shed some light on more efficient design of heat exchangers.

1. Introduction

Since Choi and Eastman [1] firstly succeeded in suspending small particles in fluids in 1995, the so-called "nanofluid" has been applied in numerous types of heat exchangers to improve the thermal performance over conventional fluids [2,3]. As it is well known, conventional fluids used for heat transfer (e.g. water, air, lubricating oil, and ethylene glycol) have very poor thermal conductivities compared with metal and metal oxides. The idea of using nanofluids in heat transfer could improve specific properties by adding solid particles with high thermal conductivity into the liquid coolant. Solid (millimetre-/micrometre-sized) particles as an additive into the base fluid has now become a popular technique for heat transfer enhancement, as reviewed in Ref. [4].

Some important heat exchangers filled with nanofluids are briefly introduced as follows. Huang et al. [5] investigated a chevron corrugated-plate heat exchanger filled with hybrid nanofluid mixture containing alumina nanoparticles and multi-walled carbon nanotubes (MWCNTs). The heat transfer and fluid flow characteristics of metallic water nanofluids in an agitated serpentine heat exchanger was experimentally studied in Ref. [6]. Hedayati et al. [7] found out that one-sided heating was most efficient at enhancing the heat transfer rate for laminar TiO_2-water nanofluid flow in a heat exchanger of parallel plate microchannel. Sundén [8] experimentally investigated the hydraulic and thermal performance of aqueous multi-walled carbon nanotube (MWCNT) nanofluids in a double-pipe helically coiled heat exchanger. Thermal performance of hydromagnetic Al_2O_3/water nanofluid inside a heat exchange equipment of vertical microannular tube was numerically analysed in Ref. [9]. A typical heat exchanger that has aroused our interests is a heat pipe with discrete heat sources [10–12]. Mixed convection heat transfer in a horizontal channel with discrete top and bottom heat sources has been investigated experimentally, and experimental results for flush mounted heat sources subjected to uniform heat flux were presented for different aspect ratios and ranges of Grashof and Reynolds numbers [13].

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Nomenclature

c	specific heat (J/kg·K)
D	mass diffusivity
dt	time step size
H	channel height (m)
h	average heat transfer coefficient (W/m^2·K)
h_f	reference average heat transfer coefficient (W/m^2·K)
k	thermal conductivity (W/m·K)
L_i	length of the channel wall (m)
n	power law index
Pr	generalized Prandtl number $\left(Pr = \frac{c_f \mu_f H^{1-n}}{k_f U_0^{1-n}}\right)$
p	pressure (Pa)
q_i	heat flux (W/m^2)
Re	Reynolds number $\left(Re = \frac{\rho_f H^n U_0^{2-n}}{\mu_f}\right)$
Sc	generalized Schmidt number $\left(Sc = \frac{\mu_f H^{1-n}}{\rho_f D_B U_0^{1-n}}\right)$
T	temperature (K)
U_0	inlet velocity (m/s)
$\mathbf{u}$ = (u, v)	velocity of nanofluid
u, v	velocity components along x and y directions, respectively (m/s)
$\mathbf{v}$	shape function vector
x, y	Cartesian coordinates along the channel plate and normal to it, respectively (m)

Greek symbols

Ω	calculation domain
μ	dynamic viscosity (Pa·s)
ϕ	nanoparticle concentration (%)
ρ	density (kg/m^3)
$\sigma_{\mathbf{u}}$	shear stress (Pa)
σ_0	power law coefficient (Pa·s^n)

Subscripts

0	inlet conditions
eff	effective
f	fluid

Inspired by the above mentioned works, our configuration of interest focuses on a horizontal parallel plate channel with multiple discrete heating and cooling regions.

Generally, nano-sized particles were suspended in Newtonian fluids. By changing the base fluids into non-Newtonian flow, however, the thermal performance of nanofluids could be significantly enhanced or weakened, which may reinforce or diminish the effects of heat exchangers [14–16]. A careful review of the literature shows that nanofluids based non-Newtonian flow is obtaining rising research attention. For example, the heat transfer of non-Newtonian nanofluids in a differentially heated square cavity [17] and in a two-dimensional (infinite depth) horizontal rectangular duct were investigated by Santra et al. [18]. Ellahi [19] examined the magnetohydrodynamic (MHD) flow of non-Newtonian nanofluid in a pipe, and the effects of MHD flow of non-Newtonian nanofluid in coaxial porous cylinders were performed by Zeeshan [20]. Inspired by previous influential works, our research focuses on a special kind of non-Newtonian nanofluids (power-law nanofluids). For instance, Islami et al. [21] studied the heat transfer and fluid flow of a non-Newtonian nanofluid, with the aqueous solution of Carboxymethyl Cellulose (CMC) as base fluid, in two dimensional parallel plate micro channel without micro mixers. Kang et al. [22] investigated the thermal convection in a nonhomogeneous nanofluid-saturated porous layer by taking into account the shear-thinning rheology, Brownian diffusion and thermophoresis of power-law nanofluids.

In our previous work [16], the heat transfer of nanofluids based power-law flow in an exchanger with several discrete heating and cooling regions has been analysed, assuming that the nanofluid was mixed uniformly. Thus, equations concerning non-uniform concentration were not taken into consideration in that work as in Ref. [12]. To get closer results to industrial practice, the influence of non-uniform nanoparticle distribution on heat transfer performance will be considered in the present study. Besides, the impacts of particle sedimentation and precipitation on fluid flow and heat transfer of nanofluids is also a focus, the importance of which has been demonstrated in the following literature. Jung et al. [23] presented an investigation of Al_2O_3 nano-particles dispersed in distilled water, ethylene glycol and ethylene glycol-distilled water mixture, and multiple correlations between nano-fluid characteristics and thermal properties have been explored. Ganji et al. [24] theoretically investigated laminar fully-developed mixed convection of alumina-water nanofluid through a vertical annulus, concentrating on controlling the nanoparticle migration and how it affects the heat transfer rate and pressure drop. Bahiraei [25] evaluated the flow and heat transfer characteristics of the suspensions of Fe_3O_4 magnetic nanoparticles in turbulent flow and considered the effects of particle migration which induces non-uniform concentration distribution in the simulation. Jing et al. [26] employed a modified population balance model of rheological law to investigate the coagulation and fragmentation of magnetic nanoparticles in nanofluids to control the heat transfer process and fluid flow. The nanofluid forced convection in the entrance region of a baffled channel was investigated by Fazeli et al. [27] where a scalar equation was added into conservation equations to reveal the migration and distribution of nanoparticles.

However, adding an equation depicting the particle concentration to the model imposes tremendous difficulty for numerical calculations with increased CPU-cycle consumption. Some methods have been employed in the literature to overcome the obstacle. Homotopy analysis method (HAM) has been employed in Ref. [28] to analyse the natural convection boundary layer flow along an inverted cone, considering the effects of the shape of nanoparticles on entropy generation. Besides, with the finite volume method coupled with the SIMPLEC algorithm, Nasiri et al. [29] studied the magnetic field effect on mixed convection heat transfer of nanofluid with linear viscosity as a function of particle volume fraction. Sheikholeslami et al. [30] presented a three-dimensional investigation on the magnetohydrodynamics nanofluids in a cubic cavity by the Lattice Boltzmann method.

Different from above investigations, the present study adopts finite element method (FEM) to solve the equations, focusing on the effects of nano-sized particle migration on the thermal performance of nanofluids in a horizontal channel with multiple regions of heating and cooling. Validation of the method used in this paper has been presented in our previous works [16,31] that it is not only suitable for solving the N-S, energy, concentration equations of Newtonian flow, but also applicable to more general cases of non-Newtonian fluids and nanofluids in complex geometries or with varying physical components.

2. Model description and mathematical formulation

Fig. 1 depicts the configuration of a horizontal parallel plate channel with four heaters and two coolers arranged symmetrically on the walls. Note that the remaining parts of the channel are