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Numerical investigation of forced convection heat transfer through microchannels with non-Newtonian nanofluids

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ABSTRACT

In this paper, convection heat transfer and laminar flow of nanofluids with non-Newtonian base fluid in a rectangular microchannel have been investigated numerically using two-phase mixture model. This research investigates the advantages of using nanoparticles in non-Newtonian fluids with particles size equal to 30 nm. The factor that makes nanoparticles feasible is the significant increase in rate of heat transfer within the fluids that are common in today's industry. The power law model is used both Newtonian and non-Newtonian fluids. The flow behavior and rate of heat transfer performance of microchannel heat sink have been taken into account by looking into the effects of Al_2O_3 nanoparticles concentrations, Peclet number and flow behavior index. Our results demonstrate significant enhancement of heat transfer of non-Newtonian fluids using nanoparticles particularly in the entrance region. By increasing the volume fraction, higher heat transfer enhancement can be observed. The thermal resistance with Peclet number of 700 and 4% volume fraction reduces approximately 27.2% with shear thinning non-Newtonian base fluid and pressure drop will increase approximately 50.7%. Further analysis on particles type effect is also implemented with Al_2O_3 and CuO nanoparticles.

1. Introduction

The liquid coolants are essential for heat transfer in many engineering equipments such as electronic devices, heat exchangers and vehicles. In recent years, many attempts has been made to minimize the scales and improve the performance of instruments. Convective heat transfer in microelectromechanical systems (MEMS) has been confirmed to be an effective method for the thermal control of these devices such as microflow sensors, microchannels heat sink (MCHS), biomedical and biochemical systems [1–3]. The advantages of MCHS consist of ability to produce very high heat transfer coefficient, compactness, high surface-to-volume ratios of microscale devices and small coolant requirements [4–6]. So far, the most common coolants in the MCHS studies have been done for Newtonian fluids such as water, ethylene glycol and so on.

Heat transfer processing of non-Newtonian fluids is encountered in various industrial sectors including chemicals, petrochemicals, polymers, and pharmaceuticals [7]. High heat transfer capacity and low pumping power of some non-Newtonian fluids make them attractive as a coolant for various applications such as microchannel heat exchangers. Non-Newtonian fluids exhibit a non-linear relation between shear stress and shear rate. The simplest model of non-Newtonian fluids is the Ostwald–de Waele power law model used for intermediate ranges of the shear rate and various fluids [8–10].

Fluid flow and heat transfer problems involving non-Newtonian fluids have been reviewed by Metzner [11], Skelland [12], Cho and Hartnett [13] and among many others. Hartnett and Kostic [14] have collected the results about laminar and turbulent fluid flow and heat transfer of non-Newtonian fluids through rectangular channels with different aspect ratios. Schechter [15] obtained velocity profiles using a variational principle, for laminar flow through rectangular ducts of various aspect ratios. Wheeler and Wissler [16] applied an overrelaxation procedure to obtain more accurate velocity distributions and friction factors for aspect ratios of 0.5, 0.75 and 1.

One approach to augment the convective heat transfer coefficient in the microchannel may be utilizing nanofluids as common fluids. Nanofluid is a suspension of solid nanoparticles (with diameter of 1–100 nm) in conventional liquids like water and oil. Depending on shape, size, and thermal properties of the solid nanoparticles, the thermal conductivity can be increased by about

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40% with low concentration (1–5% by volume) of solid nanoparticles in the mixture [17–19]. Extensive theoretical and experimental studies have been done to explain behavior of effective thermal conductivity of nanofluids. Some experimental studies [20,21] show that the measured thermal conductivity of nanofluids is much larger than the classical theoretical predictions [22]. Other experimental investigations [23,24] revealed that the thermal conductivity has not shown any anomalous enhancement and for lower volume fractions, the results agree well with the classical equations [22,25]. Many attempts have been made to formulate efficient theoretical models for the prediction of the effective thermal conductivity [26–28].

Heris et al. [29,30] studied the effects of alumina and copper oxide nanofluids on laminar heat transfer in a circular tube with considering water as a base fluid. They reported that heat transfer coefficient enhances for both nanofluids with increasing nanoparticles concentrations as well as Peclet number, and observed higher enhancement in alumina nanofluid than copper oxide.

Numerical investigations on nanofluids are carried out in general using two approaches; single-phase or two-phase approach. Single-phase approach assumes that the continuum assumption is still valid for fluids with suspended nano size particles and fluid phase and nanoparticles are in thermal and hydrodynamic equilibrium. The other approach considers a two-phase model, which encloses a better description of the fluid and the solid phases.

Since the solid particles sizes are classified as nanoparticles, they can easily fluidize and be approximately considered to behave as a fluid. However, because the effective properties of nanofluids are not known precisely, the numerical predictions of this approach depends on the effective physical properties.

Xuan and Li [31] studied the single-phase flow and heat transfer performance of nanofluids under turbulent flow in tubes. Their experimental results showed that the convective heat transfer coefficient and the Nusselt number of nanofluids increase with the Reynolds number and the volume fraction of nanoparticles under turbulent flow. They have observed about 39% increase in Nusselt number when volume fraction was increased from 0 to 2% under same Reynolds number.

The two-phase approach seems to be a better model for describing of the nanofluid heat transfer. In other words, the slip velocity between the fluid and nanoparticles might not be zero [19] due to several factors such as friction between the fluid and solid particles, Brownian forces, gravity, Brownian diffusion, sedimentation and dispersion.

Behzadmehr et al. [32] studied the turbulent forced convection of a nanofluid in a circular tube by using a two-phase approach. They implemented the two-phase mixture model for the first time to study nanofluid. They examined the axial evolution of the flow field and fully developed velocity profiles at different Reynolds numbers. Their comparison with the experimental results showed that the mixture model is more precise than the single-phase model. Bianco et al. [33] numerically worked on developing laminar forced convection flow of a water–Al_2O_3 nanofluid in a circular tube. They found that the maximum difference in the average heat transfer coefficient between single-phase and two-phase models results was approximately 11%. They concluded that heat transfer enhancement increases with the particle volume concentration as well as shear stress values.

In recent years, the rapid development of engineering technologies has contributed significantly to the convective heat transfer enhancement of nanofluids with Newtonian base fluids. However, the effect of nanoparticles on the convective heat transfer in the non-Newtonian base fluids has not been investigated yet. The objective of this study is to numerically investigate the convective heat transfer coefficient of nanofluid with non-Newtonian base fluid in the rectangular microchannel in laminar flow regime. Initially, heat is supplied to the silicon substrate through the heating area, then is removed by flowing non-Newtonian nanofluid through a microchannel. Three dimensional steady state flow is considered for the rectangular microchannel heated uniformly from the bottom. Throughout this research, the base fluid is a non-Newtonian Ostwald–de Waele power law model with spherical nanoparticles with the diameter of 30 nm. Two-phase mixture model approach is employed to evaluate the laminar forced convection flow by considering the temperature variable thermophysical properties. The numerical simulation results are compared with other works presented in literature for flow of non-Newtonian base fluid in microchannel. This paper is structured in the following manner. Section 2 outlining the model formulation, numerical method and simulation conditions, Section 3 discussing the numerical results, and finally, in Section 4, a summary of the main conclusions are presented.

2. Mathematical modeling

2.1. Governing equations

Laminar forced convection of a nanofluid consisting of non-Newtonian base fluid with nanoparticles has been considered. In this numerical investigation, the gravitation force is considered as an important parameter. Because of symmetry and for simplicity and reduction of calculation time, only one microchannel is selected and analyzed as computational domain. It is clear that the heat sink exhibits geometrical symmetries. Due to the heat sink module chosen in this study, planes of symmetry can also be identified for the heat transfer part of the problem. With the above simplifications, only one microchannel is modeled as shown in Fig. 1b.

The geometrical configuration in this simulation work is depicted schematically in Fig. 1. Due to the heat sink module chosen in this study, symmetrical planes are used for the heat transfer part of the problem.

The nanofluid flows through the one rectangular microchannel with imposing of constant heat flux to the silicon substrate at the bottom part of the solid microchannel. The top surface is assumed to be adiabatic. A complete description of thermal behavior of microchannel include three dimensional conduction analysis in solid parts of microchannel and three dimensional solutions of conservation equations of non-Newtonian nanofluid under steady state conditions. For temperature profiles in solid microchannel, it is necessary to solve the conduction equation within solid microchannel with neglecting the effect of dissipation and pressure work. Heat sink performance is commonly measured by its thermal resistance that is defined as below [34].

$$R_{\mathrm{th}} = \frac{T_{\mathrm{w,max}} - T_{\mathrm{f,in}}}{q_{\mathrm{w}}}$$

$$\begin{aligned} R_{\mathrm{th}} &= \frac{\Delta T_{\max}}{q_{\mathrm{w}}} = \frac{T_{\mathrm{w,max}} - T_{\mathrm{f,in}}}{q_{\mathrm{w}}} \\ &= \frac{\left(T_{\mathrm{w,max}} - T_{\mathrm{f,out}}\right) + \left(T_{\mathrm{f,out}} - T_{\mathrm{f,in}}\right)}{q_{\mathrm{w}}} = \frac{1}{\bar{h}A_{\mathrm{fin}}} + \frac{1}{\dot{m}C_p} \\ &= R_{\mathrm{con}} + R_{\mathrm{cap}} \end{aligned} \tag{1}$$

where $T_{\mathrm{w,max}}$, $T_{\mathrm{f,in}}$, $T_{\mathrm{f,out}}$, q_{w}, R_{con} and R_{cap} are the maximum temperature of surface (wall), the inlet fluid temperature, the outlet fluid temperature, the heat flux at the heating area, convective and capacitive resistance, respectively.