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Non-Newtonian nanofluid in a micro planar sudden expansion considering variable properties

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ABSTRACT

The heat transfer and flow pattern of Al_2O_3-water nanofluid in a micro planar sudden expansion with constant heat flux boundary conditions are numerically studied. The Al_2O_3-water nanofluid is treated as a single phase non-Newtonian fluid with variable physical properties and the power-law rheology is adopted to describe the characteristics of the flow, in which the flow behavior index depend on the nanoparticle volume fraction. A systematic study of the Al_2O_3-water nanofluid for a wide range of generalized Reynolds number, $50 \leq Re_{gen} \leq 500$, and nanoparticle volume fraction $0\% \leq \varphi \leq 3\%$ is presented. The critical generalized Reynolds number at which flow bifurcation occurs is carefully studied and the heat transfer enhancement due to the non-Newtonian rheology is reported. It is shown that the flow bifurcation is delayed when the nanoparticle volume fraction increases and is advanced as the boundary heat transfer rate increases. The heat transfer deterioration brought by the recirculation area is reduced under a higher nanoparticle volume fraction and the reduction ratio increases with the generalized Reynolds number. The non-Newtonian model results are also compared with the results using a Newtonian model, which indicates that there will be a huge overestimate on the system pressure drop if Newtonian model is taken.

1. Introduction

Nanofluid is a dilute suspension of solid nanometer-size particles and fibers dispersed in a conventional fluid (i.e., water, oil etc.). These particles can be metallic or nonmetallic, such as Al_2O_3, SiO_2, Cu, CuO, ZnO and TiO_2 [1]. Nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients compared to those of base fluids like oil or water [2–4]. Researchers reported that nanofluids can clearly exhibit enhanced thermal conductivity, which goes up with increasing nanoparticle volume fraction. Nanofluids often appear better heat transfer performance because of the high thermal conductivity, thus they are widely used to improve the system efficiency. In order to use nanofluids for small scale cooling techniques such as integrated circuits and micro-electro mechanical systems, the investigation on flow and heat transfer of nanofluids in microstructures like microtubes and microchannels is imperatively needed. The system geometries include micro tubes [5], microchannels [6–8] and microchannels of a sudden change (i.e. backward-facing steps [9] and forward-facing steps [10]).

The separation in the fluid flow can be generated from a sudden change in flow geometry. The planar sudden expansion plays an important role in the design of many engineering applications where heating or cooling is required. When a Newtonian fluid flows at low to moderate Reynolds number in a planar channel and encounters a sudden expansion, flow separation occurs resulting in a pair of symmetric recirculating eddies along the downstream walls. When Reynolds number is increased above the critical value, the vortexes become asymmetric, and gradually a third eddy is formed downstream of the smallest of the two main vortexes [11]. The bifurcation phenomenon, consisting of a transition from the symmetric to the asymmetric flow, has great impact on the flow and heat transfer performance of the system and thus is of great interests.

In many realistic situations, the fluids flowing through the devices are non-Newtonian and show complex rheological behavior. A non-Newtonian fluid is one whose flow curve (shear stress versus

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shear rate) is non-linear or does not pass through the origin, i.e. where the apparent viscosity (shear stress divided by shear rate) is not constant at a given temperature and pressure but is dependent on flow conditions such as flow geometry, shear rate, etc. and sometimes even on the kinematic history of the fluid element under consideration. Specifically, they can exhibit shear-thinning or shear-thickening viscosity depending on the type of fluid.

In most related works, nanofluids are treated as homogeneous single-phase fluids (with the assumption that the nanoparticles are uniformly distributed in base fluids). Thus, the most common way is to use the macroscopic results from the numerous existed studies on the flow and heat transfer of fluids in large scale structures. Kherbeet et al. [10] used Newtonian model to investigate the flow and heat transfer performance of Al_2O_3-water nanofluids in a microchannel of a forward-facing step and set experiment for validation. Although the experimental and numerical results are generally in good agreement, there still exists a gap between the pressure drop obtained from the experiment and that of the simulation. These results indicate that the macroscopic regulations may not be simply extended to apply for microscopic problems due to the appearance of some special phenomena with the shrinkage of characteristic length, e.g. the fluid rheology. Some scholars used two-phase model to numerically simulate the flow and heat transfer performance of nanofluid. Sheikholeslami. et al. [12] used Fourth-order Runge–Kutta method to analyze thermal radiation on magnetohydrodynamic nanofluid. Eslamian [13] clarified the role of thermophoresis of Rayleigh-Benard laminar natural convection by using a two-phase Lattice Boltzmann Method. In these studies, the convectional fluid is treated as a continuous phase and the nanoparticle is presented by its volume friction. The Brownian motion and thermophoresis effects can be studied in this way, but the fluid rheological behavior is still not considered.

Rheological behavior of nanofluids affects pressure drop of nanofluids. Additionally it gives an idea of nanoparticle structuring, which can be helpful in predicting the thermal conductivity of nanofluids. One simplified way as has already been used in many works [14–16] is to treat nanofluids as a Newtonian fluid with modified physical properties. However, some experimental results have shown that the Newtonian model may not be accurate enough for describing the behavior of some particular nanofluids. Some researchers observed a shear-thinning fluid behavior [17] and some reported that the increasing nanoparticle volume fraction enhance the shear-thinning behavior [18]. The shear-thinning behavior has been found in different species of nanofluids, including Cu-water [17,19], carbon nanotube-water [18], Al_2O_3-water [20–22] and TiO_2-water [23–25]. Although different kinds of nanofluids show non-Newtonian behavior, it has to be emphasized that there are still many Newtonian nanofluids. All the suspensions containing SiO_2 nanoparticles show Newtonian behavior [26,27]. Al_2O_3-water nanofluid show non-Newtonian behavior while Al_2O_3-EG and Al_2O_3-PG behave as Newtonian fluid [28,29]. Water-based nanofluid containing micro-sized Al_2O_3 particle exhibits shear thinning behavior. Tseng and Wu [21] investigated Al_2O_3-water nanofluids with the particle diameter $d = 37$ nm and volumetric solid concentrations from 1% to 16%, and concluded that the suspension generally showed a transition from shear-thinning to shear–-thickening as the shear rate exceeded a certain critical. Also, this critical value of shear rate increased with the rise of nanoparticle concentration.

Some scholars have done remarkable works on the numerical simulation of non-Newtonian nanofluids. J. Niu et al. [5] theoretically studied the slip-flow and heat transfer of a non-Newtonian nanofluid in a microtube, and concluded that the heat transfer rate of the nanofluid in the microtube can be enhanced due to the non-Newtonian rheology and slip boundary effects. GH.R. Kefayati [30] used Finite Difference Lattice Boltzmann Method (FDLBM) to study the heat transfer and entropy generation on laminar natural convection of non-Newtonian Cu-water nanofluids in the presence of an external horizontal magnetic field in a square cavity. Results indicate that the augmentation of the power-law index causes heat transfer to drop in the absence of the magnetic field, by contrast, the heat transfer increases with the rise of power-law index in the presence of the magnetic field. Li et al. [31] used power-law model to numerically simulate laminar forced convection nanofluids in a horizontal parallel plate. Ellahi et al. [32] used the homotopy analysis method (HAM) to get the analytical solutions of non-Newtonian nanofluids with Reynolds' model and Vogel's model. Later this method were used to gave the analytical solutions of the magnetohydrodynamic (MHD) flow of non-Newtonian nanofluid in a pipe [33] and nanofluid flow through composite stenosed arteries with permeable walls [34]. Some recent researches have been focused on different types of non-Newtonian nanofluid such as Jeffrey nanofluid [35] and Oldroyd-B nanofluid [36].

The objective of this work is to investigate the heat transfer and flow pattern of Al_2O_3-water non-Newtonian nanofluid in a micro planar sudden expansion. Al_2O_3-water nanofluid is chosen because it has identifiable non-Newtonian behavior and a rich set of experimental data. According to the author's knowledge, the flow bifurcation and heat transfer enhancement of the specific model is still lacking. In the present study, we present a systematic study of the Al_2O_3-water nanofluid for a wide range of generalized Reynolds number, $50 \le Re_{gen} \le 500$, and nanoparticle volume fraction $0\% \le \varphi \le 3\%$. The boundary conditions are set to be different values of constant heat flux rate. The symmetry breaking flow bifurcation is carefully studied and the heat transfer enhancement due to the non-Newtonian rheology is reported. We also compare the non-Newtonian model results with the results using a Newtonian model.

2. Mathematical models

2.1. Problem description

Laminar convection flows in the planar sudden expansion are numerically simulated. The problem under study is illustrated schematically in Fig. 1a, and the nomenclature used to refer to the various characteristic lengths of the vortices is illustrated in Fig. 1b. A two-dimensional, planar channel of width h has a sudden expansion to a second channel of width H. The center of the coordinate axes system lies at the bottom of the geometry expansion plane. The upstream channel has a length $L_a = 50\,h$ and that of the downstream channel is $L_b = 200\,h$. The both side of the downstream boundary wall has a constant heat flux of q_w. The inlet is located far enough to ensure that the inlet fluid flow be fully developed before the expansion. Similarly, the outlet is located far away from the region where the separating flow regions occur.

The upstream width of the duct (h) is 100 μm; its downstream width (H) is 300 μm, and the expansion ratio is $ER = H/h = 3$. Cold nanofluid of temperature T_0 flows from the left to the right. The nanofluid is a mixture of water and solid aluminum oxide particles of 30 nm diameter. The nanoparticles are of uniform shape and size. The nanofluid is incompressible and the flow is laminar. Also the nanofluid is treated as homogeneous single-phase fluids (with the assumption that the nanoparticles are uniformly distributed in base fluids; the liquid and solid are in thermal equilibrium). The thermophysical properties of the nanofluid are assumed to be temperature dependent. The effect of buoyancy is neglected, since it is not significant in comparison with the microchannel flow.