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Research Paper

Effects of non-Newtonian behaviour on the thermal performance of nanofluids in a horizontal channel with discrete regions of heating and cooling

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HIGHLIGHTS

- The potential of nanofluid based power-law flow is proposed in heat exchangers.
- Flow intensity and heat transfer can be adjusted by using power-law based fluids.
- A numerical study on exchanger with discrete heating regions confirms the proposal.

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ABSTRACT

A numerical simulation is performed to investigate laminar forced convection nanofluid based non-Newtonian flow in a horizontal parallel plate with discrete regions of heating and cooling. Water, pseudoplastic and dilatant fluids are used as working base fluids. Power-law modelling is adopted to predict the effect of non-Newtonian behaviour on the thermal performance of nanofluids in a channel with heating (cooling) regions placed symmetrically on walls, and the remaining surfaces are considered adiabatic. The velocity and temperature fields, heat transfer coefficient ratio, and pressure drop are investigated, considering the influence of power-law index n, nanoparticle volume fraction ϕ, Reynolds number, and generalized Prandtl number. It is observed that the velocity and temperature of nanofluids may increase or decrease considerably by changing the base power-law fluids. The results reveal that nanofluids based on dilatant flow are more sensitive to the environmental heat flux than those based on pseudoplastic fluid. Furthermore, the pressure drop increases as the power-law index rises. The findings demonstrate that the presence of non-Newtonian effects in nanofluids can lead to improvement and optimization in the thermal performance of channels, which suggests the potential of nanofluid based power-law flow in industrial equipment heating and cooling applications.

1. Introduction

Thermal control and management have always been the most effective factors in the safe and correct operation of industrial equipment, such as frequency convertors, high-power amplifiers, and power supplies [1]. It is important to remove generated heat because high temperatures in precision equipment can adversely affect operation. In heat-dissipating equipment, different shapes and sizes of heat pipes, as useful and efficient heat exchangers, have often been used to provide steady and suitable thermal conditions [2]. In 1995, Choi and Eastman [3] were the first to suspend tiny particles in fluids, which has been shown to improve the thermal performance of conventional fluids. Later, this so-called "nanofluid" was applied in various types of heat pipes to increase the thermal conductivity; some examples are summarized in Refs. [4,5]. Furthermore, nanofluids have been used in a critical type of heat exchanger: heat pipes with discrete heat sources [1,6,7]. In a representative example, Mashaei et al. performed a numerical investigation on the laminar forced convection flow of Al_2O_3–water nanofluid in a porous parallel plate channel with discrete heat sources that were placed on the bottom wall of the channel [7]. Inspired by these works, a horizontal parallel plate channel with several discrete heating and cooling regions is our configuration of interest.

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By changing conventional fluids into nanofluids, the thermal performance of heat pipes can be improved. Furthermore, if the thermal conductivity of a nanofluid cannot meet the requirements of an industrial process, it might seem that the only possible optimization method is to add more nano-sized particles into the liquid, although many nanoparticles (such as gold [8] and silver [9]) are expensive. Noting this limitation and considering the vital application of heat pipes, it should be pointed out that there are relatively few reports in the literature devoted to improving the thermal performance of a nanofluid by changing its base fluid. In our past research [10,11], it was found that by changing the base fluids to achieve non-Newtonian flow, the heat transfer of nanofluids was significantly enhanced or weakened, which in turn reinforced or diminished the effects of heat exchangers.

Although it is a reasonable hypothesis to assume a thoroughly homogeneous nanofluid to be a Newtonian fluid (for example, water-γ Al_2O_3 and ethylene glycol-γ Al_2O_3 mixtures [12]), the non-Newtonian effect of a base fluid on nanoparticles and the interaction between suspended nanoparticles and liquid cannot be ignored in some intricate industrial areas such as nuclear cooling applications, micro-electromechanical systems, electronics and instrumentation, and biomedical applications (e.g., nano-drug delivery, cancer therapeutics, and cryopreservation) [13]. A review of the literature indicates that non-Newtonian nanofluids have so far obtained some attention. Santra et al. have conducted a series of studies considering the heat transfer of non-Newtonian nanofluids in a differentially heated square cavity [14,15] and in a two-dimensional (infinite depth) horizontal rectangular duct [16]. Other researchers have focused on the magneto hydrodynamic flow of non-Newtonian nanofluids. Ellahi et al. [13,17,18] and Zeeshan et al. [19] analysed the effects of magneto hydrodynamic, slip boundary conditions, and variable viscosities (namely Reynolds' model and Vogel's model) on non-Newtonian nanofluids in coaxial porous cylinders and pipes. Porous media were also taken into account.

The present article investigates the non-Newtonian characteristics of nanofluids and presents a potential way to reduce the cost of nano-sized particles that have been widely used in the industry to enhance heat transfer. The commonly used nanoparticle types include chemically stable metals (e.g., copper), metal oxides (e.g., alumina and silica), oxide ceramics (e.g., Al_2O_3 and CuO), carbon in various forms (e.g., carbon nanotubes) and other functionalized nanoparticles [13,20], which are not inexpensive. However, the cost of some non-Newtonian fluids is much less than that of most nano-sized particles. For example, carboxymethyl cellulose aqueous solution is relatively inexpensive but exhibits varying power-law rheology as a function of solution concentration [10,11].

Motivated by these conditions, this work has been undertaken to analyse the flow and heat transfer of laminar forced convection of non-Newtonian nanofluids in a horizontal parallel plate channel with several discrete heating and cooling regions. The finite element method is used to solve the governing equations. The data and figures representing the velocity and temperature fields, heat transfer coefficient ratio, and pressure drop between different types of non-Newtonian nanofluids are compared and provided for researchers in the fields of heat exchanger design and equipment cooling.

2. Model description and mathematical formulation

The configuration of the horizontal parallel plate channel with height H investigated in this paper is shown in Fig. 1. Four heaters and two coolers are arranged symmetrically on the walls of the channel. The remaining parts of the plates are isolated. The following assumptions are made for the laminar forced convection nanofluids flowing through the channel: the incompressible fluid flow and heat transfer are all in two-dimensional steady state; the nanoparticles and base fluid move with similar velocity in the absence of gravity and buoyancy effects; the nanoparticles and base fluids will not interact chemically; and (as the most important factor in this research) the nanofluid is a power-law non-Newtonian fluid. The last situation occurs when an anisotropic mixture exhibits non-Newtonian behaviour or when nanoparticles are placed in a power-law based fluid. Thus, the conclusions of the paper are appropriate for two cases: a nanofluid (the base fluid of which is Newtonian flow) which exhibits non-Newtonian power-law behaviour [21] and a power-law fluid that does not change its rheological behaviour when nanoparticles are placed in it.

By combining the assumptions above, the general governing equations are as follows:

Continuity:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

Momentum [22]:

$$\rho_f\left((\mathbf{u}\cdot\nabla)\mathbf{u}\right) = -\nabla p + \nabla\cdot(\mu_{eff}\sigma_u) \tag{2}$$

where ρ_f is the fluid density; $\mathbf{u} = (u, v)$ represents the velocity of the nanofluid, where u denotes the horizontal velocity and v the vertical velocity; and p is the hydrostatic pressure. In the model, the formula for $\sigma_\mathbf{u}$ is

$$\sigma_\mathbf{u} = \left(2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right)^{\frac{n-1}{2}} (\nabla\mathbf{u} + \nabla\mathbf{u}^T) \tag{3}$$

where n is the power-law index. Fluids with $0 < n < 1$ are pseudoplastic non-Newtonian fluids whereas $n > 1$ describes dilatant fluids. The condition $n = 1$ corresponds to Newtonian fluids including water [23,24]. To focus on the impact of the particle loading parameter

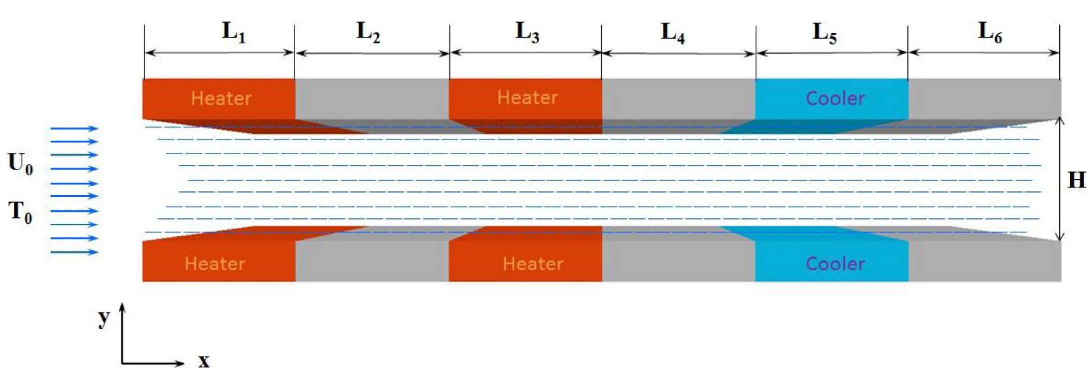

Fig. 1. Nanofluids flowing through parallel plate channel with discrete heaters and coolers.