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Mixed convection heat transfer of double immiscible fluids in functional gradient material preparation

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ABSTRACT

Double immiscible flow has been extensively emerged in science and technology. In this research, mixed convection heat transfer of double immiscible fluids in a vertical parallel channel is investigated. One layer is pure fluid while the other is nanofluid. The effective kinematic viscosity and the effective thermal conductivity are regarded as linear functions of the nanoparticle loading parameter. A method of translation and scaling the computational domain for calculating the coupled equations subject to eight boundary conditions is developed. This method is applicable no matter the widths of the two regions are equal or not. Two interesting phenomena are revealed: the nanofluid with lower particle loading parameter is a better option for higher effectiveness of fluid driving; adding more nanoparticles in one layer can enhance heat transfer of both layers.

1. Introduction

In the process of preparing material or coating, two-phase flow appears or fluid is stratified due to the density or other reason. Thus, the subject of double layers of immiscible flow has been extensively emerged in geophysics, petroleum industry, magnetic-fluid dynamics, and plasma-physics [1]. The design and investigation on the double-fluid transport system include, but not limited to, cooling equipment, heat exchangers, space machines, nuclear reactors, etc. [2]. Most multi-layer flows occur in three different situations. First, in the processes of co-extrusion and lubricated transport, many polymer-typed additives are added into the molten polymer layer for better flow stability in the high-throughput extrusion process [3]. These additives function as lubricants, which lie in layers between the walls of a duct and the transported fluid [4]. Second, the film coating process involves a multi-layer, where a different layer is used on each fluid substrate [5]. Third, the convention of driving a non-conducting fluid by a conducting fluid using the viscous shear stress is widely used in the electro-osmotic driven flow in microfluidics devices [6].

The difficulty to investigate the multi-fluid flow situation focuses on the interaction between different kinds of fluids, especially in the same geometry. Some pioneers have so far obtained some progress: Packham and Shail [7] investigated two immiscible stratified laminar flow layers in a horizontal pipe. Kumar and Pop et al. [8] dealt with two laminar free-convection fully-developed flow layers in a vertical channel, in which one layer is a micropolar fluid and the other is a viscous fluid.

To increase the toughness and strength of the materials, researchers add nano-sized particles into the melting state of materials, which brings nanofluids to industrial production and preparation. Some fascinating research on nanofluids are as follows: Sheikholeslami et al. [9] analyzed the hydrothermal problem of the magnetic nanofluid over a plate considering the thermal radiation. They adopted the Runge-Kutta method to get the solutions of ordinary differential equations. Shirvan et al. [10] have adopted two phase mixture model to investigate the sensitivity analysis of heat transfer in a double-pipe heat exchanger full of Al_2O_3 nanofluid by means of the Response Surface Methodology. Kefayati [11] have investigated the entropy generation and heat transfer of convection laminar nanofluids constituted by water and nanoparticles of copper under the influence of external magnetic fields in square cavities by the method of Finite Difference Lattice Boltzmann. Bahiraei [12] studied the performance and hydrothermal characteristics of biologically produced nanofluids in a miniature counter-flow double-tube heat exchanger considering the particle migration. Sheremet et al. [13] carried a numerical investigation on the natural convective heat transfer of nanofluids in porous wavy cavities. He adopted the two-phase nanofluid model considering the Brownian diffusion and the thermophoresis diffusion. Garoosi et al. [14] presented a numerical analysis on the

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Nomenclature

A	a constant
b	thermal expansion coefficient ratio (β_2/β_1)
Br	Brinkman number $(\mu_1 U_0^2/(k_1(\tilde{T}_2 - \tilde{T}_1)))$
C_p	fluid specific heat
$F(\phi), G(\phi)$	functions of the particle loading parameter
GR	dimensionless parameter $(= Gr/Re)$
Gr	Grashoff number $(g\beta_1(\tilde{T}_2 - \tilde{T}_1)h^3/\nu_1^2)$
g	acceleration due to gravity
h	channel width ratio (h_2/h_1)
h_i	channel width of the region i
k	ratio of the thermal conductivities (k_1/k_2)
k_i	thermal conductivity of the fluid in the region i
m	ratio of the viscosities (μ_1/μ_2)
P	pressure
p	ratio of the densities (ρ_2/ρ_1)
Re	Reynolds number $(U_0 h/\nu_1)$
T	temperature
$\tilde{T}_1, \tilde{T}_2$	temperature of the boundaries
T_0	$\frac{\tilde{T}_1+\tilde{T}_2}{2}$
U	velocity
U_0	reference velocity $(\Omega A h^2/\mu_1)$
u_i	non-dimensional velocity of the region i
X, Y	Cartesian coordinates along the plate and normal to it, respectively
y	non-dimensional Cartesian coordinates normal to the plate
$\tilde{y}$	a defined independent variable $\tilde{y} = y - 1$ in Case I and $\tilde{y} = y/h$ in Case II
z_i	a series of defined variable denoting the $(i-1)$-th derivative of u with respect to y
z_i'	z_{i+1}

Greek symbols

α	thermal diffusivity
β	coefficient of the thermal expansion
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
θ	non-dimensional temperature
ϕ	particle loading parameter

Subscripts

1 and 2	refer to quantities for Region I and II, respectively
eff	refers to the effective quantities of nanofluids

natural convection nanofluid in a heat exchanger, and revealed the impacts of the arrangement and the numbers of cold and hot pipes on the thermal performance of the heat exchanger. Sheikholeslami and Ganji [15] utilized the Control Volume based Finite Element Method to investigate the ferrofluid flow under the influence of an external magnetic field, and the fluid is contained within a semi annulus enclosure with sinusoidal hot walls.

Having this in mind as well as referring to former literature on double layer fluids, our present work focuses on adding nano-sized particles into only one layer of two-layer immiscible fluids. We also noticed that some predecessors' inspiring studies have involved the study of nanofluids in two-layer flow. In a vertical channel, a non-Newtonian third-grade nanofluid bordering a non-Newtonian third-grade pure fluid was investigated in a work by Farooq and Liao et al. [16]. Khan et al. [5] dealt with a clear Eyring-Powell fluid adjacent to a nano-Eyring-Powell fluid as the two fluids are filled in two equal regions in a vertical channel. However, compared with the predecessors, the present research is not only focusing on whether the addition of nanoparticles can enhance the heat transfer, but also revealing the volume fraction of nanoparticles can affect the fluid driving effectiveness of double-layer fluids.

Above all, our aim is to investigate mixed convective velocity and temperature distributions of double layer immiscible fluid flow in a vertical parallel plate channel. The governing differential equations are fourth-order, and eight boundary conditions have involved, which has greatly increased the difficulty of calculation. Despite of various semi analytical and numerical approaches for nanofluids simulation [17,18], such as Lattice Boltzmann method [19,20], two-phase approaches (Eulerian-Lagrangian approach, and Eulerian-Eulerian approach), thermal dispersion model, and so forth, we carried out a fast numerical technique to solve the coupled equations and boundary conditions in this paper. The method is flexible no matter the regions of multiple-layer fluids are equal or not. Moreover, the proposed numerical techniques in this paper will be easily extended to solving the governing equations of multiple-layer fluids in more complex cases.

2. Mathematical formulation

The configuration of two immiscible layers flowing through an infinite vertical parallel channel is shown as Fig. 1. Consider the two flow layers possessing different physical properties. The wall temperatures keep at constant. The region $-h_1 \leqslant Y \leqslant 0$ is filled with a viscous fluid processing viscosity μ_1, density ρ_1, thermal expansion coefficient β_1, and thermal conductivity k_1. The region $0 \leqslant Y \leqslant h_2$ contains a nanofluid with density ρ_2, and thermal expansion coefficient β_2. Assume that the nanoparticles move consistently with the base fluid. The effective viscosity μ_{eff} and the effective thermal conductivity k_{eff} are determined as functions of the particle loading parameter ϕ as Refs. [21,22]

$$\mu_{eff} = \mu_2 F(\phi) \tag{1}$$

$$k_{eff} = k_2 G(\phi) \tag{2}$$

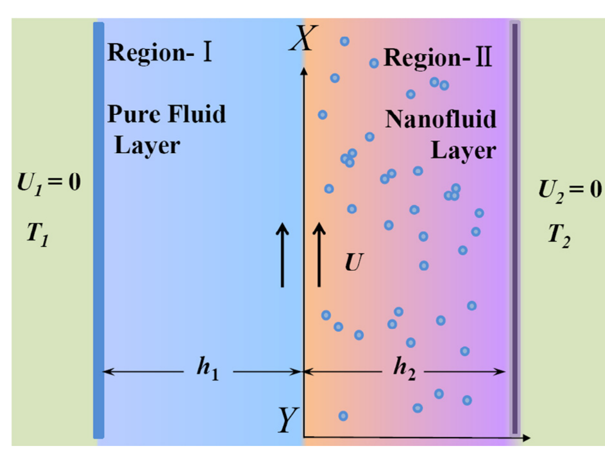

Fig. 1. Two-layer flow consisting of viscous fluid and nanofluid.