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Numerical analysis of natural convective flow and heat transfer of nanofluids in a vertical rectangular duct using Darcy-Forchheimer-Brinkman model

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ABSTRACT

In this paper, natural convective flow and heat transfer of nanofluids in a vertical rectangular duct filled with porous matrix is investigated. The Darcy-Forchheimer-Brinkman model is used to represent the fluid transport within the porous medium covering the parametric ranges of $1 \leq Gr \leq 25,0 \leq Br \leq 8$, and $0.0001 \leq Da \leq 100$. Also, pure water and five different types of nanofluids (*Cu*, diamond, TiO_2, *Ag* and SiO_2) are used with a volume fraction range of $0\% \leq Ø \leq 0.2\%$. The governing nonlinear, coupled partial differential equations for the two-dimensional laminar, steady flow and heat transfer are solved numerically by a finite difference method with second order accuracy. It is found that the heat transfer is enhanced due to the use of a nanofluid. Further, it is noticed that an increase in the Darcy or Grashof or Brinkman numbers, or the aspect ratio parameter increase the flow and heat transfer characteristics; whereas the inertial or the viscosity ratio parameters reduce the flow and heat transfer characteristics. It is observed from 2-D graphs that the fluid rise up from the middle portion of the vertical wall and flow down along the two horizontal walls forming symmetric rolls with clockwise and counter-clockwise rotation inside the cavity. The temperature contours in 2-D are smooth curves which span the entire enclosure, and they are generally symmetry with respect to the horizontal symmetric line. The results obtained reveal many interesting behaviors that warrant further study on the heat transfer enhancement due to the nanofluids.

1. Introduction

A nanofluid refers to a fluid that contains particles with dimensions less than 100 nm. The base fluid or dispersing medium can be aqueous or non-aqueous in nature. Typical nanometer-sized particles are metals, oxides, carbides, nitrides or carbon nanotubes. Their shapes may be spheres, discs or rods. The study of nanofluids is an important branch of nanotechnology, since it has potential applications in transportation and electronic cooling (Shalkevich et al. [1], Wu et al. [2]), biomedicine (Xu et al. [3]), oil drilling (Ju et al. [4]), nano-structure fabrication (DeVries et al. [5], Kane et al. [6]) and nanocomposites (Guo et al. [7], Lu et al. [8]). Its fundamental science spans colloidal science, surface chemistry, fluid mechanics and materials science. Since early 1990s, many exciting new phenomena and results have been reported on the "magic" power of nanoparticles. The area of nanofluids saw a similar excitement. There have been reports on abnormal thermal conductivity of a fluid comprising nanoparticle, effective diffusion of nanoparticle through the cells of live bodies, super-magnetism and quantum dots effect of nanoparticle. The thermal conduction of nanofluids has attracted the most attention and more than one thousand papers have been published in this area. Choi and Alivisatos [9] found that at a loading of less than 2 wt % of Cu nanoparticle (with an average diameter of 10 nm), the thermal conductivity of the base fluid was increased by 40%. This has profound impact on energy efficiency in coolants (Eastman [10]). Heat transfer in nanofluids has been surveyed recently in a review article by Das and Choi [11] and a book by Das et al. [12]. Recently Umavathi and Chamkha [13] studied convection flow in a vertical rectangular duct filled with purely viscous fluid.

Nanofluids in porous media constitute an emerging topic; the review of recent literature points out to at least two possible applications. Porous foam and micro-channel heat sinks (used for

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Nomenclature

A	aspect ratio
a	horizontal distance
b	vertical distance
BR	Brinkman number
C_F	porous media inertia coefficient
Da	Darcy number
g	acceleration due to gravity
I	dimensionless porous medium inertia coefficient
K	thermal conductivity of the fluid
m	viscosity ratio
Nx, Ny	grid number in computational domain
T	fluid temperature
T_0	reference temperature
T_1, T_2	temperatures of the walls of the duct
U, V, W	velocity components
u, v, w	dimensionless velocity components
X, Y, Z	cartesian coordinates
x, y, z	dimensionless space coordinates

Greek letters

β_T	coefficient of thermal expansion
κ	permeability of the porous media
ρ_0	density of the fluid
ν	kinematic viscosity
μ	viscosity
θ	dimensionless temperature
ϕ	solid volume fraction
Φ	source parameter

Subscript

nf	thermo-physical properties of the nanofluid
f	base fluid
s	nano-solid-particles

electronic cooling) are usually modeled and optimized utilizing the porous medium approach (see Kim et al. [14], Kim and Kuznetsov [15]). The utilization of nanofluids for cooling such micro-channel heat sinks has been recently suggested by Tsai and Chein [16] and Ghazvini and Shokouhmand [17]. Modeling of such heat sinks requires understanding of the fundamentals of nanofluid convection in porous media. Another relevant area to nanofluid convection in porous media is the utilization of nanoparticle hyperthermia for cancer treatment (Salloum et al. [18,19]). The objective is to induce the maximum damage to the tumor (this requires evaluating the temperature of at least 90% of the tumor above 43 °C) with a minimum damage to the normal tissue. Since a living tissue is a type of fluid-saturated porous medium, in fact, many medical studies use agarose gels with porous structures similar to human tissue for in vitro experiments; see, for example, Salloum et al. [20], the development of optimal protocols for this treatment again requires a fundamental understanding of nanofluid convection in porous media. For experimental study of convection flow in porous media using nanofluids, few studies have been carried out. Hajipour and Molaei Dehkordi [21] were the first who experimentally and numerically investigated the nanofluid mixed convective heat transfer inside a vertical channel partly filled with porous metal foam. The obtained results show that nanofluid flow in the presence of porous metal foams can improve the heat-transfer rate and may have applications in industrial. Nazari et al. [22] investigated the forced convective heat transfer due to flow of nanofluid through a circular tube filled with an aluminum open-cell porous media with porosity of 50% experimentally. Casting around space holder with an average size of 3–5 mm diameter materials method was used for fabricating the metal foam. They found that using the porous medium inside the tube leads to a significant enhancement of heat transfer in comparison with the empty tube. Hwang et al. [23] quantified the pressure drop and convective heat transfer coefficient of water-based Al_2O_3 nanofluids flowing through a uniformly heated circular tube in the fully developed laminar flow regime. According to the experimental results, they found a good agreement with analytical predictions from the Darcy's equation for single-phase flow for the nanofluid's friction factor. Xuan and Roetzel [24] presented two different approaches to define some fundamentals for predicting the convective heat transfer coefficient of nanofluids under the assumption that they behaved like a single-phase liquid rather than a normal solid-liquid mixture. In their study, the effects of thermal dispersion and transport properties of the nanofluid were covered. The first model treated as a single-phase and the other model treated as a multi-phase fluid and dispersed fluid. It was assumed that liquid phase and the particles being in thermal equilibrium state were devoid of slip velocity between them. The nanofluid acted as a common pure liquid. This implied that the all equation of energy continuity, and motion for a single-phase fluid had been applied directly to the nanofluid.

In a very recent review paper by Sheikholeslami and Ganji [25] explained clearly about the concept of single phase and two-phase models. In their paper they mention that single-phase approach is simpler and more computationally efficient. Using the single-phase model Sheikholeslami et al. [26] studied magnetic effect on unsteady nanofluid flow and heat transfer using Buongiorno model. Sheikholeslami et al. [27] extended their study considering magnetic field dependent viscosity effect on free convection of magnetic nanofluid using single phase model. Using Lattice Boltzmann method Sheikholeslami and Ganji [28] studied the entropy generation of nanofluid in the presence of magnetic field considering single-phase model. The same authors Sheikholeslami and Ganji [29] again considering single-phase model using control volume based finite element method analysed the influence of and external magnetic field on ferrofluid flow and heat transfer in a semi annulus enclosure with sinusoidal hot wall. Sheikholeslami et al. [30] also considered the two-phase model to study the effect of thermal radiation on magnetohydrodynamics nanofluid flow between tow horizontal rotating plates. Further, many studies in the literature have performed the numerical simulation using single-phase assumption and reported acceptable results for the heat transfer and hydrodynamic properties of the flow. A comprehensive survey of convective transport in nanofluids was made by Buongiorno [31], who later proposed a model incorporating the effects of Brownian diffusion and thermophoresis.

The Darcy model, which assumes proportionality between the velocity and the pressure gradient, has been extensively used to investigate a number of interesting fluid and heat transfer problems associated with heated bodies embedded in fluid-saturated porous media. The model however, is valid only for slow flows through porous media with low permeability (see Nakayama et al. [32]). At higher flow rates or in highly porous media, there is a departure from the linear law and inertial effects become important. In terms of the Reynolds number based on the typical particle diameter (say), it has been found that the flow becomes non-Darcian when the Reynolds number exceeds unity (see Bear [33]). Physically, this departure is believed to be due to flow separation within the medium, while