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Original Research Paper

Heatline visualization of natural convection in a trapezoidal cavity partly filled with nanofluid porous layer and partly with non-Newtonian fluid layer

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ABSTRACT

The problem of natural convection in a trapezoidal cavity partly filled with nanofluid porous layer and partly with non-Newtonian fluid layer is visualized by heatline. Water-based nanofluids with silver or copper or alumina or titania nanoparticles are chosen for investigation. The governing equations are solved numerically using the Finite Volume Method (FVM) over a wide range of Rayleigh number ($Ra = 10^5$ and 10^6), Darcy number ($10^{-5} \leqslant Da \leqslant 10^{-1}$), nanoparticle volume fraction ($0 \leqslant \phi \leqslant 0.2$), power-law index ($0.6 \leqslant n \leqslant 1.4$), porous layer thickness ($0.3 \leqslant S \leqslant 0.7$), the side wall inclination angle ($0^\circ \leqslant \varphi \leqslant 21.8^\circ$) and the inclination angle of the cavity ($0^\circ \leqslant \omega \leqslant 90^\circ$). Explanation for the influence of various above mentioned parameters on streamlines, isotherms and overall heat transfer is provided on the basis of thermal conductivities of nanoparticles, water and porous medium. It is shown that convection increases remarkably by the addition of silver–water nanofluid and the heat transfer rate is affected by the inclination angle of the cavity variation. The results have possible applications in heat-removal and heat-storage fluid-saturated porous systems.

1. Introduction

Natural convection fluid flow and heat transfer in a closed cavity partly filled with a porous layer and partly with a fluid layer have received considerable attention over the past few years. The prominence of this issue is due to the broad spectrum of environmental problems or industrial applications such as ground-water pollution, benthic boundary layers, geothermal systems, storage of nuclear waste, dendritic solidification, drying processes, thermal insulation, spreading on porous substrates and filtration processes. In order to understand the transfers in composite domains, some authors have considered the natural convection and heat transfer in cavities where the layers are confined either vertically or horizontally.

The first attempts to study experimentally and analytically the natural convection flow and heat transfer between a porous media and a homogeneous fluid by focusing on the boundary condition at the fluid/porous interface were made by Beavers and Joseph [1]. Nield [2] applied the linear stability analysis of natural convection in a configuration composed by a fluid layer overlying a homogeneous porous medium with uniform heating from below. The Darcy model was applied to study the high value of Rayleigh in natural convection in a fluid overlaying a porous bed [3]. According to Beckermann et al. [4], the Brinkman–Forchheimer–extended Darcy was adopted to investigate the natural convection flow and heat transfer between a fluid layer and a porous layer inside a rectangular enclosure. Study of the horizontal partition was carried out by Chen and Chen [5] through investigating experimentally the convective stability in a superposed fluid and porous layer. Chen and Chen [6] discussed the problem of nonlinear computational investigation of thermal convection in a superposed fluid and porous layer using Darcy–Brinkman–Forchheimer model. Gobin et al. [7] analyzed the particular subclass of such problems where natural convection occurs in a confined enclosure, partially filled with a porous medium.

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Nomenclature

Cp	specific heat capacity (J/kg K)
Da	Darcy number
g	gravitational acceleration (m/s^2)
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium
n	power-law index
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
S	porous layer thickness parameter (m)
T	temperature (K)
u, v	velocity components in the x-direction and y-direction (m/s)
U, V	dimensionless velocity components in the X-direction and Y-direction
x, y & X, Y	space coordinates & dimensionless space coordinates

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (1/K)
ε	the consistency coefficient
ν	kinematic viscosity (m^2 s^{-1})
ϕ	solid volume fraction
φ	the side wall inclination angle
ψ & Ψ	stream function & dimensionless stream function (m^2 s^{-1})
θ	dimensionless temperature
ω	the inclination angle of the cavity
ρ	density (kg/m^3)
μ	dynamic viscosity (N s/m^2)

Subscript

c	cold
bf	base fluid
f	fluid
h	hot
nf	nanofluid
sp	solid nanoparticle

Most of the above mentioned studies focused on the natural convection heat transfer in square/rectangular cavities. In reality, natural convection in a differentially heated enclosure is a prototype of many industrial application and in particular, a trapezoidal enclosure has received considerable attention because of its applicability in various fields. The moderately concentrating solar energy collector is an important example involving a trapezoidal geometry. The study of convective flow in a trapezoidal geometry is more difficult than that of square/rectangular cavities due to the presence of sloping walls. In general, the mesh nodes do not lie along the sloping walls, and consequently, from a programming and computational point of view, the effort required for determining flow characteristic increases significantly. Lee [8] firstly performed a numerical and experimental flow visualization study and heat transfer in a differently heated trapezoidal cavity filled with pure fluid. Karyakin [9] has simulated the flow and temperature fields for various inclination angles of the sloping wall and showed that the heat transfer rate increase with the increasing angle of the sloping wall. However, no work has been reported in literature on natural convection fluid flow and heat transfer in trapezoidal cavity partly filled with a porous medium.

Thermal fluids are very important for heat transfer in many industrial applications. The low thermal conductivity of conventional heat transfer fluids such as water and oils is a primary limitation in enhancing the performance and the compactness of many engineering electronic devices. Solid typically has a higher thermal conductivity than liquids. For example, copper (Cu) has a thermal conductivity of 700 time greater than that of water and 3000 greater than engine oil. An innovative and new technique to enhance heat transfer is using solid particles in the base fluid (i.e. nanofluids) in the range of sizes 10–50 nm. Due to small sizes and very large specific surface areas of the nanoparticles, nanofluids have superior properties like high thermal conductivity, minimal clogging in flow passages, longterm stability and homogeneity. Thus, nanofluids have a wide range of potential applications such as electronics, automotive, and nuclear applications where improved heat transfer or efficient heat dissipation is required. Saleh et al. [10] conducted for the first time a numerical study to solve the problem of natural convection in a trapezoidal cavity filled with water–Cu and water–Al_2O_3 nanofluids. Garoosi et al. [11] considered numerically the effects of several pairs of heaters and coolers on natural convection of nanofluids in a square cavity. Ganji and Malvandi [12] applied the uniform magnetic field on natural convection of nanofluids inside a vertical cavity. By using modified Buongiorno's model, Malvandi and Ganji [13] discussed the effects of magnetic field and slip boundary on free convection inside a vertical cavity filled with alumina/water nanofluid. Very recently, Garoosi et al. [14] studied numerically the natural convection heat transfer of nanofluid in a square cavity using finite volume discretization method. Nevertheless, the study of natural convection fluid flow and heat transfer in a trapezoidal cavity partially filled with porous medium has not been undertaken yet.

Most of the previous studies have investigated the Newtonian fluids with the focus on clear fluid media as mentioned in above works. On the other hand, relatively limited work has been directed to the natural convection of non-Newtonian fluids. The flow characteristics of several industrial fluids such as multi-phase mixtures (oil–water emulsions, froths and foams, etc.), paints and biological fluids (blood, synovial fluid, salvia, etc.) can be sorted into the non-Newtonian fluids. Also, the non-Newtonian fluids have attracted a lot of attentions due to their importance in several industrial applications such as, compact heat exchangers, polymer engineering, electronic cooling systems, geophysical systems, chemical reactor design, etc. When the relation between the shear stress and the shear rate is nonlinear (the shear stress is proportional to the strain rate), a fluid converts to non-Newtonian fluid. The non-Newtonian fluids in natural convection filled with clear fluid have received considerable attention by many researchers. Bin Kim et al. [15] have studied the effect of unsteady natural convection in a square enclosure with non-Newtonian fluid. Lamsaadi et al. [16] investigated analytically and numerically the effect of steady natural convection in a shallow rectangular cavity with non-Newtonian power law fluids. Turan et al. [17] have considered the two-dimensional steady-state simulations of laminar natural convection in a square enclosure filled with non-Newtonian fluids and differentially heated sidewalls subjected to constant wall temperatures. Habibi Matin et al. [18] discussed the steady natural