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Transient natural convection heat transfer in nanoliquid-saturated porous oblique cavity using thermal non-equilibrium model

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ABSTRACT

The problem of transient natural convection heat transfer in a nanoliquid-saturated porous oblique cavity is studied numerically using the finite difference method. The hot left wall of the cavity is maintained at a constant temperature and so is the cold right wall. The horizontal walls allow no heat transfer to the surrounding. The Darcy law is used along with the Boussinesq approximation for the flow. The heat transfer equations are those of a two-phase medium, one for the nanoliquid and another for the porous medium. Water-based nanoliquids with Ag or Cu or Al_2O_3 or TiO_2 nanoparticles are chosen for investigation. The governing parameters of this study are the Rayleigh number ($10^2 \le Ra \leqslant 10^4$), modified conductivity ratio ($0.1 \le \gamma \leqslant 1000$), inter-phase heat transfer ($0.1 \le H \leqslant 1000$), inclination angle of the sloping walls ($-\frac{\pi}{3} \le \omega \le \frac{\pi}{3}$), volume fraction of nanoparticles ($0 \le \varphi \le 0.2$) and dimensionless time ($0 \le \tau \leqslant 0.1$). The assumption of local thermal non-equilibrium leads to an enhanced heat transfer situation in nanoliquids saturating a porous medium compared to that in a porous medium with local thermal equilibrium. Explanation for the observed influences of various parameters on streamlines, isotherms and weighted average Nusselt number is given in terms of thermophysical properties of four nanoparticles, water and porous medium. It is shown that the strength of the flow circulation increases for the relative concentration of nanoliquid with the increment of the inclination angle to the positive direction.

1. Introduction

Nanoliquid as a working medium has been considered by many researchers for the simple reason that due to the presence of nanoparticles, the thermal conductivity of medium gets enhanced and so nanoliquid seems a good candidate for heat removal mechanisms in practical, thermal, liquid-based applications. Porous medium has been a favorite in heat storage applications. Individually, in these two areas, there has been a surge in research activity concerning natural convective heat transfer. There is a good number of excellent research papers and books in present time that serve as testimony to this wave of interest. Wang and Mujumdar [1] presented an excellent survey on the heat transfer characteristics of nanoparticles in forced and free convection flows. Mahian et al. [2] exhibited a useful review on the investigation of the nanofluids and its applications in solar thermal engineering systems and the effects of nanofluids on the performance of solar collectors and solar water. In view of many different thermal problems possible to be investigated in the above two media, we restrict our survey of literature to natural convection in enclosures. The very first comprehensive work on natural convection in nanoliquids occupying enclosures is that by Khanafer et al. [3]. The work of Tiwari and Das [4] considers a lid-driven flow of nanoliquid in a differentially heated square cavity. Jou and Tzeng [5] considered natural convective heat transfer in nanoliquids occupying a rectangular enclosure. Santra et al. [6] investigated enhanced heat transfer in Ostwald de Waele model-based nanoliquid housed in a differentially heated cavity. Nield and Kuznetsov [7] studied analytically the effects of Brownian motion and thermophoresis of nanoliquid on the onset of convection in a porous medium layer saturated by a nanoliquid. Jahanshahi et al. [8] made an experimental investigation of heat transfer in a cavity filled with a water–silicondioxide nanoliquid. Alloui et al. [9] picked the water–allumina nanoliquid for investigation in a shallow rectangular cavity using a finite volume method and a water–copperoxide nanoliquid medium. Chand and

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Nomenclature

Cp	specific heat capacity (J/kg K)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	inter-phase heat transfer coefficient
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium (m^2)
L	length of enclosure (m)
Nu	Nusselt number
Nu_{wa}	weighted average Nusselt number
Ra	Rayleigh number
t	time (s)
T	temperature (K)
u, v	dimensional velocity components in the x- and y-directions respectively (m/s)
U, V	dimensionless velocity components in the X- and Y-directions respectively
x, y	dimensional space coordinates
X, Y	dimensionless space coordinates

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (1/K)
γ	modified conductivity ratio
Γ	thermal diffusivity ratio
ω	inclination angle of the sloping wall
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2 s^{-1})
ϕ	volume fraction of nanoparticles
φ	solid volume fraction of fluid-saturated porous medium
ψ	dimensional stream function (m^2 s^{-1})
Ψ	dimensionless stream function
τ	dimensionless time
η	dimensionless scaled variable ($\eta = \frac{Y}{\cos(\omega)}$)
θ	dimensional temperature
ξ	dimensionless scaled variable ($\xi = X - Y\tan(\omega)$)
ρ	density (kg/m^3)

Subscript

c	cold
bl	base liquid
h	hot
nl	nanoliquid
np	nanoparticles
s	solid

Rana [10] analytically studied the oscillatory convection in a horizontal porous medium layer saturated by a nanoliquid where Darcy model was applied. Aminfar et al. [11] numerically investigated the buoyancy driven convection of nanoliquids in a floating zone.

Chand and Rana [12] analytically investigated the effect of rotation on the onset of convection in a horizontal porous medium layer saturated by a nanoliquid where Darcy–Brinkman model was used. They found that the values of Rayleigh number are clearly decreased with the increasing of the porosity parameter. Meanwhile, Kandasamy et al. [13] studied the effects of Thermophoresis and Brownian motion on MHD laminar fluid flow of a nanoliquid in the presence of thermal stratification due to solar radiation. Garoosi et al. [14] numerically investigated the natural convection in a square cavity filled with nanoliquids and several pairs of heaters and coolers by using finite volume discretization method. Heris et al. [15] made a comparative experimental study on natural convective heat transfer in turbine oil-based nanoliquid in an inclined cavity using different metal oxide nanoparticles. Recently, Malvandi and Ganji [16] numerically investigated the chemical and slip effects on natural convection inside a vertical cavity filled with alumina/water nanoliquid by using Runge–Kutta–Fehlberg scheme. They concluded that the concentration of the nanoparticles was higher near the cold wall compared to that of the hot wall. Compared to the study of natural convection in nanoliquids, the work on natural convection in porous cavities is exhaustive. An excellent survey was made on the fundamental topic of flows in porous media with an important issue from diverse fields such as energy, civil, biotechnology, chemical, and environmental engineering by Bejan [17]. The book by Ingham and Pop [18] presents an inclusive account of available information in the field of transport phenomena in porous media and the area of fluid mechanics and heat transfer which is closely related to energy utilization and conservation. Basak et al. [19] numerically investigated the effects of various thermal boundary conditions on natural convection in a square cavity filled with a porous medium. A recent comprehensive literature survey concerning convection in porous media is given by [20].

Several studies placed attention on natural convection in square/rectangular cavities with or without nanoparticles in liquids. In reality, natural convection in a differentially heated cavity is a prototype for numerous industrial applications and specifically, oblique cavity has received considerable attention because of its applicability in various fields. Studying natural convection heat transfer in an oblique geometry is 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 efforts required for setting flow characteristics rise significantly. With non-rectangular enclosures being important in practical engineering applications such as in solar collectors or heat exchangers with different shaped duct constructions, Baytas and Pop [21] used an oblique cavity in their study of convection. Han and Hyun [22] studied numerically the buoyant convection in an oblique cavity filled with a porous medium by using finite volume method. Recently, Nayak et al. [23] numerically considered the study of mixed convection in an oblique cavity filled with nanoliquid. In addition to the possible applications of such systems in heat removal and heat storage problems, of relevance to the present work are the works of Wu et al. [24,25] who showed how the porous wall filters the small particles. They considered the distribution characteristics of exhaust gases and soot particles using Lagrangian continuous random walk model.

Most of the previous studies considered the natural convection heat transfer in a porous medium in local thermodynamic equilibrium where the fluid temperature is equal to the solid temperature. Meanwhile, the case where the fluid temperature is different to the solid temperature, we call this as the local thermal non-equilibrium model. Many studies have considered the thermal equilibrium model in a porous medium, while the non-equilibrium model has not received much attention. Haddad et al. [26] studied the validity of the local thermal equilibrium assumption in natural convection in a porous medium along a vertical flat plate. Their study is based on the two-phase model and used the