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Original Research Paper

The effect of inclination angle and hot wall configuration on Cu-water nanofluid natural convection inside a porous square cavity

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ABSTRACT

Natural Convection of Cu-water nanofluid in an inclined cavity filled with porous media has been investigated using two-phase mixture model. The co-effect of cavity's inclination angle, heater configuration, use of nanofluid and porous media on heat transfer enhancement has been studied with detailed investigation of the decision variables effect (Rayleigh number, Darcy number, inclination angle, and volume fraction of Cu nanoparticles) on heat transfer characteristics. The investigation considers the laminar flow for natural convection ($10^4 \leqslant Ra \leqslant 10^6$). Darcy-Brinckman-Forchheimer model has been used as for the simulation of porous media and two-phase mixture model has been applied to model the behavior of nanofluid. In accordance it has been shown that simultaneous use of nanofluid with porous media in weak convection flows is beneficial, but for strong natural convection fields that would be unfavorable and decreases heat transfer rate. It has been concluded that the effect of inclination angle highly depends on the hot wall location as in some states having the square cavity inclined would be of benefit while in another case the total heat transfer would decline. The results show that proper selection of heater configuration (side wall or corner heating) and inclination angle inline with nanofluid concentration and porous media properties can highly affect heat transfer performance. Furthermore, optimal solutions might exist for different conditions.

1. Introduction

Given the importance of heat transfer enhancement in numerous facets of engineering, myriad studies have been done ameliorating natural convective heat transfer as one of the principal phenomena in nature and engineering [1–4]. This buoyancy-induced convection is vastly present in engineering applications like electronic equipment [5,6], and heat-exchange systems [7,8]. Hence, investigating the primary factors affecting the natural convective heat transfer and introducing the best operational conditions should be of significant consideration.

One way to improve the natural convective heat transfer rate in cavities is implementing porous media. This, however, induces drag forces which decelerate the fluid, can be noticeably useful in conditions in which the conduction heat transfer is dominant over convection heat transfer. Having this solid matrix with its structured pores offers two significant advantages over the implementation of fins. Those are, larger fluid-solid contact area, as well as the erratic motion of the fluid through the pores, that make heat transfer more effective than conventional fins. Considering the usefulness of porous media, in order to have an accurate computation of the associated physics and geometry, precise models of energy and momentum transport should be applied [9]. Darcy's model as the first description of transport phenomena in porous media, however simple, fails to represent high speed flows in porous media. Later, it was followed by modifications by Brinkman and Forchheimer, and now Darcy-Brinkman-Forchheimer model is commonly implemented for mathematical description of fluid flow in porous materials [9].

Another beneficial approach regarding the augmentation of natural convective heat transfer is employing the suspension of the fluid and solid nanoparticles known as nanofluids, rather than using the low heat conducting base fluid [10]. Considerable mathematical models have been adduced in the literature trying to model the behavior of nanofluids, and they all can be classified as single-phase and two-phase models. Single-phase models rely on advancing new correlations to stand for effective properties of the nanofluid as a single-phase slurry comprises the base fluid and nanoparticles. Hence, the nanofluid suspension is regarded

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Nomenclature

a	acceleration (m s^{-2})
C_p	specific heat (J kg^{-1} K^{-1})
C_d	drag coefficient
Da	Darcy number
d_p	nanoparticles diameter (m)
f_{drag}	drag function
Gr	Grashof number
g	acceleration due to gravity (m s^{-2})
H	cavity length
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_b	Boltzmann constant (J K^{-1})
Nu	Nusselt number
P	pressure (Nm^{-2})
Pr	Prandtl number
q''	uniform wall heat flux (W m^{-2})
Ra	Rayleigh number
Re_B	Reynolds number (Brownian-motion)
Re_P	Reynolds number (particle)
T	temperature (K)
T_{fr}	freezing point of the base fluid (K)
u_B	Brownian velocity of nanoparticles (m s^{-1})
$\vec{V}$	velocity vector (m s^{-1})

Greek symbols

α	inclination angle (m^2 s^{-1})
α_f	thermal diffusivity (m^2 s^{-1})
β	thermal expansion coefficient (K^{-1})
ε	porosity
φ	volume fraction
κ	permeability of porous medium (m^2)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
θ	dimensionless temperature
ρ	density (kg m^{-3})
Ψ	dimensionless stream function

Subscripts

avg	average
eff	effective
c	cold wall
dr	drift
f	fuid
s	solid (porous media)
h	hot wall
k	summation index
m	mixture (nanofluid)
p	nano-particles

as a new homogeneous fluid with modified properties. Two-phase models (such as two-phase mixture [11,12], Eulerian-Eulerian [13,14], Eulerian-Lagrangian [15,16] and double-diffusive [17,18]) in which nanoparticles and the base fluid can be at different velocities, have been found out to be more accurate than single-phase models [19,20]. For instance, Göktepe et al. [21] had a comparative investigation of single- and two-phase models for nanofluid convection at the entrance of a uniformly heated tube and have found out that two-phase models predict convective heat transfer coefficient and friction factor more accurately at the entry region. Among different two-phase models for nanofluid flow simulation, two-phase mixture can resolve problems investigating low concentration nanofluid flows with acceptable accuracy and lower computational costs. Rahimi-Gorji et al.'s [22] investigation on nanofluid flow between two vacillated parallel plates in the presence of magnetic field suggests that for their case of study CuO gives better values for skin friction coefficient and Nusselt number than Al_2O_3. Also, higher Nusselt numbers and lower skin friction coefficients are achieved by increment in nanofluid volume fraction.

Considering the effect of nanoparticle's size, nanoparticle's concentration, and various mixtures of different base fluids and nanoparticles on heat transfer, Pourmehran et al. [23] investigated the heat transfer and flow characteristics of nanofluid flow by a stretching sheet in the presence of an external magnetic field and reported that for their case of study as the nanoparticle concentration increases, the reduced Nusselt number dwindles. Also, as reported by the authors, the TiO_2-ethylene glycol 50% gives higher reduced Nusselt number and lower skin friction coefficient compared to other mixtures.

Another study by Rahimi-Gorji et al. [24] on heat transfer analysis of microchannel heat sink using several nanofluids indicates that the greater the nanoparticles volume fraction becomes, the more significant Brownian movement of the particles is at hand, leading to less difference of temperature between the coolant and the wall.

Many researchers have considered the natural convection in various shapes e.g. triangular cavities [25–29], trapezoidal enclosures [30–32], square cavities [26,27], curved cavities [33] and wavy-walled cavities as well [34,35].

There are studies in which the main focus has been the effect of thermal boundary conditions on heat transfer rate [36–39]. Alsabery et al. [40] addressed the effects of finite wall thickness and sinusoidal heating on convection in a nanofluid-saturated local thermal non-equilibrium (LTNE) porous cavity and reported that the overall heat transfer is significantly increased with the relative non-uniform heating. Some researchers have investigated the effect of thermal source and sink locations on heat transfer. Türkoglu and Yücel [41] investigated natural convection in a square enclosure with a partially heater and cooler on vertical walls having the location of them changed. Mahmoodi et al. [42] simulated the magneto-natural convection in square cavities with five different thermal source-sink configurations regarding their relative locations. In their study, the maximum heat transfer occurred in the square cavity with its source on the bottom and the sink located on the left wall and the case of having a cold wall at the bottom and the hot wall at the top gave the minimum heat transfer rate. In a study conducted by Chen and Chen [43], the natural convection in a square enclosure with two different configurations of a partially hot wall were investigated. Cheikh et al. [44] investigated the natural convection in an air-filled 2D square enclosure heated with a constant source from below and with different configurations of sink on other walls. Ghasemi and Siavashi [45] used LBM to investigate the effect of different linear temperature distribution of side walls on heat transfer characteristics of nanofluid inside a porous cavity.

Gravity, as the main factor causing natural convection, can be even more effective in inclined cavities. Thus, the case of having natural convection in cavities investigated in different inclination angles was interesting to some researchers [18,46,47]. Kefayati [48,49] investigated the double-diffusive natural convection of non-Newtonian power-law fluids in an inclined porous cavity

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