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Nanofluid and porous fins effect on natural convection and entropy generation of flow inside a cavity

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ABSTRACT

In the present study, natural convection of Cu-water nanofluid in a cavity with an array of porous fins on its hot wall has been numerically analyzed using two-phase approach. Use of porous fins, instead of solid ones, improves conduction while could have negligible effect on convection as flow can pass through them. Therefore, the effects of the number of fins and their length on heat transfer enhancement and entropy generation are scrutinized. The study has been conducted for the certain pertinent parameters of Rayleigh number (Ra = 10^4 to 10^6), Darcy number (Da = 10^{-1} to 10^{-4}), and the nanoparticle volume fraction (φ = 0 to 0.04) and results are investigated in terms of heat transfer, entropy generation and performance coefficient (PEC). Numerical results indicate that adding porous fins with a high Darcy number improves heat transfer while fins with a low Darcy number can weaken the convection and decline Nusselt number. In strong flow fields an increase in either the length or the number of fins has insignificant effect on Nu. Also, low concentration of nanoparticles enhances the heat transfer more than high values of nanoparticles. On the other hand, entropy generation decreases by increasing the number of fins and PEC enhances by using porous fins in most of the studied cases. PEC of pure fluid is higher than the nanofluid at low Ra numbers, while opposite fact is observed for high Ra values.

1. Introduction

Nanofluids are colloidal suspension of nano-scale particles in a base fluid with improved properties which are primarily employed for their thermal characteristics in various engineering equipment such as chemical reactors, heat exchangers, micro-electromechanical systems, solar collectors, enhanced oil recovery, fuel cells and more [1–9]. Natural convection is the main mode of heat transfer in a large number of the mentioned applications. Accordingly, natural convection in enclosures is the subject of various engineering problems and different research studies have been conducted to investigate this problem when the cavity is filled with a nanofluid [10–16]. Kefayati [17] used finite difference lattice Boltzmann method to analyze heat transfer and entropy generation on laminar natural convection of non-Newtonian nanofluids in the presence of an external horizontal magnetic field in a square cavity. Based on results of that study, increasing nanoparticles and Hartmann number enhances and declines heat transfer, respectively. Kefayati [18] also analyzed the effect of magnetic field on mixed convection in a two sided lid-driven cavity filled with non-Newtonian nanofluid using FDLBM method. Solomon et al. [19] studied natural convection of Al_2O_3 -Ethylene glycol/water nanofluids in a differentially heated cavity filled with porous materials. The main achievement of their study is that the presence of a nanofluid with volume concentration of 0.05% enhances the heat transfer performance of porous cavity, while the other concentrations of nanofluids deteriorate the performance. Shirvan et al. [20] performed a numerical analysis on natural convection in a wavy surface square cavity filled with Cu-water nanofluid. Armaghani et al. [21] presented numerical study of natural convection heat transfer and entropy generation of water alumina nanofluid in baffled L-shaped cavity. Purusothaman et al. [22] investigated a numerical analysis of 3D natural convection equipment cooling with a 3×3 array of isothermal heaters mounted on one vertical wall of the nanofluid filled enclosure. Sheikholeslami [23] used lattice Boltzmann method to simulate free convection of nanofluid in an open cavity at the presence of magnetic field. Bondareva et al. [24] performed a numerical analysis of laminar natural convection with entropy generation in a partially heated open triangular cavity filled with a Cu-water nanofluid. Selimefendigil and Öztop [25] used the finite element

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method to simulate conjugate natural convection–conduction heat transfer in an inclined partitioned cavity filled with different nanofluids on different sides. They found that the average heat transfer enhances with Grashof number, solid particles' volume fraction and the thermal conductivity ratio of the partition. They also performed a numerical study of MHD mixed convection in a nanofluid filled lid driven square enclosure with a rotating cylinder [26].

Use of porous media can improve conduction in presence of convection since fluid can pass through it. On the other hand, high heat transfer rates in small sizes are important in industrial applications, so recently simultaneous use of porous media and nanofluids has been studied in a large number of convection problems [27–30]. Siavashi et al. [31] used a nanofluid and a porous layer to enhance heat tranfer of forced convection flow inside an annulus. Afterward, they used porous ribs with a nanofluid in the same geometry and found the optimal working conditions [32]. Hashemi et al. [33] investigated natural convection of Cu-water micropolar nanofluid at the presence of the heat generation in a porous enclosure. They found that Darcy number increment has a light effect on micro-rotation of particles. Sheremet et al. [34] presented a numerical analysis on free convection performance in a wavy cavity filled with porous media and a nanofluid. They used two-phase model including the Brownian diffusion and thermophoresis effects for nanofluid transport. The main achievement of their study is that presence of local heat source has an efficient influence on heat transfer and fluid flow. Siavashi et al. [35] numerically investigated steady double-diffusive natural convection flow in inclined porous cavities including internal thermal and solutal sources. Xu et al. [36] used lattice Boltzmann method to investigate the double-diffusive natural convection around a heated cylinder in an enclosure filled with a porous medium. They found that the flow undergoes steady state, unsteady doubling periodic oscillation, quasi-periodic oscillation and non-periodic oscillation when Darcy number is varied from 10^{-4} to 10^{-2}. Sheikholeslami and Ganji [27] performed a numerical simulation to analyze convective heat transfer of Fe_3O_4-water ferrofluid in a porous cavity with external magnetic source. Ghasemi and Siavashi [37] performed lattice Boltzmann simulation to investigate natural convection in a porous cavity filled with Cu-water nanofluid under different linear temperature distributions on side walls. They also extended their investigation to simulate MHD natural convection of Cu-water nanofluid in a square porous enclosure, considering temperature dependence of viscosity and viscous dissipation with different porous to fluid thermal conductivity ratios [38]. Chen et al. [39] used lattice Boltzmann method to perform REV (representative elementary volume) scale simulation of double-diffusive natural convection in a cavity with a porous medium. Kefayati performed FDLBM simulation of double-diffusive natural convection of non-Newtonian power-law fluids in an inclined porous cavity considering Soret and Dufour effects and studied the fluid flow, heat transfer and entropy generation [40,41]. Selimefendigil et al. [42] numerically investigated mixed convection of CuO-water nanofluid in a partitioned square cavity including porous layers and an adiabatic rotating cylinder.

For a lot of engineering applications such as chemical sciences, energy, heat recoveries, surface studies and so on, high heat transfer rates in a small size are demanded. To meet this need, fins and extended surfaces can be used, and extensive researches have been carried out in this area. Hatami [43] investigated a numerical study on natural convection heat transfer of nanofluids in a rectangular cavity with two heated fins. They found that Nusselt number increases for larger fins. Ma and Xu [44] numerically investigated an unsteady natural convection and heat transfer in a differentially heated cavity with a fin. Dependence of the unsteady flow on Rayleigh number and the fin position is analyzed using a simple scaling analysis around the fin. Gao et al. [45] proposed a lattice Boltzmann model to simulate melting of phase change materials in porous media with a conducting fin. They found that heat transfer and melting speed enhance by adding fins and increasing their length. Porous fins has lower weight and pressure loss compared to solid fins, and also solid-fluid contact surface is more in porous fins. Therefore porous fins are efficient and recently more attentions have been paid to them. Gorla et al. [46] analyzed the effects of radiation and convection heat transfer in porous fins. Their results showed that the radiation part has an important share in heat transfer. Hatami et al. [47] presented heat transfer and temperature distribution equations for circular convective–radiative porous fins. They focused on improvement of the thermal efficiency of fins by defining different section shapes. Selimefendigil et al. [48] performed a numerical simulation of heat transfer from a square cavity in the presence of a thin inclined adiabatic fin using inputs–outputs generated from a CFD code with a fuzzy based identification procedure. They also numerically analyzed the effect of an upper wall mounted adiabatic thin fin on laminar pulsating flow in a backward facing step [49].

Porous media cause resistance against fluid flow and weaken convection while it improves conduction. Therefore, using porous fins is an efficient way to have strong convection and conduction. There are lots of research studies in literature about natural convection in cavities with fins, but a few works have been done about porous fins, and analysis of their arrangement in a cavity has not been investigated so far. In this study natural convection of nanofluid in a cavity with an array of porous fins is numerically investigated. To achieve better accuracy, two-phase mixture model is used for nanofluid flow. In addition, to find the optimal conditions entropy generation study is performed and a performance analysis, based on simultaneous application of the first and second laws of thermodynamics, is presented. Effects of various parameters including Rayleigh and Darcy numbers, length and number of fins and nanofluid volume fraction on fluid flow and heat transfer in investigated.

2. Problem description

Present study investigates the effect of porous fins on natural convection of Cu-water nanofluid inside a 2D enclosure. Schematic of the studied geometry and its boundary conditions, as a closed square cavity with length of H, equipped with porous fins with length of L, is shown in Fig. 1. The left and right walls are at constant temperature of T_h (hot) and T_c (cold), respectively, while the upper and bottom walls are assumed to be adiabatic. The porous fins with constant thickness of 0.04H, thermal conductivity of $k_s = 10k_{bf}$ and porosity of 0.9 are arranged equally spaced on the hot wall, and effects of fins' length (L_f/H = 0.3, 0.6 and 0.9) and their number (N_f = 0, 1, 2 and 3) on heat transfer and entropy generation characteristics are investigated for various nanofluid concentrations (φ = 0–0.04), Rayleigh (Ra = 10^4–10^6) and Darcy (Da = 10^{-1}–10^{-4}) numbers. Boussinesq approximation is used for bouyancy driven flow. Fluid flow inside the cavity is steady and laminar and the fluid is assumed to be Newtonian. Cu nanoparticles have the spherical shape with diameter of 20 nm. All the base fluid, nanoparticles and the porous regions are considered to be in local thermal equilibrium (LTE). Thermo-physical properties of the base fluid and Cu nanopartilces are summarized in Table 1.

3. Mathematical modeling

3.1. Governing equations

Two-phase mixture model for nanofluid flow modeling is used as a consequence of its satisfactory accuracy and computational

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