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Magnetohydrodynamic buoyancy-driven heat transfer in a cylindrical–triangular annulus filled by Cu–water nanofluid using CVFEM

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ABSTRACT

In this paper, effect of magnetic field on free convection heat transfer in a horizontal cylindrical–triangular annulus filled with Cu–water nanofluid is investigated numerically. The governing equations of fluid flow and heat transfer are derived in terms of stream function–vorticity formulation. The control volume based finite element method (CVFEM) is employed to deal with these equations using a linear triangular grid system. Theoretical models of Maxwell-Garnetts (MG) and Brinkman are used to simulate the presence of nanoparticles in base fluid. The effects of Magnetic field, Rayleigh number, nanoparticles and annulus radius ratio on streamlines, isotherm and heat transfer are investigated. The results indicate that the fluid flow is suppressed by the retarding effect of electromagnetic force and as Hartmann number increases, Nusselt number decreases. It is also found that the average Nusselt number is an increasing function of nanoparticle volume fraction, Rayleigh number and aspect ratio. Furthermore, enhancement in heat transfer caused by nanofluid, increases with increase of Hartmann number while it decreases with augment of Rayleigh number.

1. Introduction

One of the best ways to enhance heat transfer rate and so improve performance of hydrodynamic heat transport equipment is utilization of nanofluids. Conventional heat transfer fluids such as water, oil and ethylene glycol (EG) possess low thermal conductivity values thus limiting their utilization in challenging conditions. One of the ways to overcome this problem is by adding solid nanoparticles with high thermal conductivity in the fluid. The resulting fluid is a suspension of the solid nanoparticle in the base fluid which shows better ability in heat transfer. The developments of nanotechnology and surface science have removed primary problems related to nanofluid application such as sedimentation, cohesion, corrosion of nanoparticles and abrasion of equipment which occurred in solid–liquid mixtures with millimeter or micrometer particles. The thermal conductivities of nanofluids are expected to be greater than base fluid [1–3]. After dispersing metallic or non-metallic nanoparticles with typical sizes of less than 100 nm in base fluids, it triggers some mechanisms in the fluid which causes to improve the ability of the heat transfer such as interfacial layer at the particle/liquid interface [4,5], Brownian motion of the particles [6,7], nanoparticle clustering [8,9], temperature and nanoparticle size [10, 11], and nanoparticle shape and volume fraction [12,13]. In the past several years, many researchers have focused on the influence of nanofluid applications in heat transfer and fluid flow both numerically and experimentally [14–20]. Aminossadati and Ghasemi [21] studied natural convection in a two-dimensional square cavity filled with a water–CuO nanofluid with two pairs of heat source–sink numerically. They dealt with governing equations by control volume approach using SIMPLE algorithm and examined effects of Rayleigh number and nanoparticle volume fraction on heat transfer rate. They deduced that regardless of position of the pairs of source–sink, the heat transfer rate increases with an increase of the Rayleigh number and the solid volume fraction. Nasrin and Parvin [22] investigated free convection heat transfer of water–based Cu nanofluid in a trapezoidal enclosure. They considered different values of aspect ratio and Prandtl number in their study and found that the average Nusselt number is a dominant function of Prandtl number as well as cavity aspect ratio and nanofluid volume fraction. Mahmoodi and Hashemi [23] examined effects of adding Cu nanoparticles to water on natural convection heat transfer within C-shaped enclosures. Their results showed that the rate of heat transfer increased with increase in volume fraction of the nanoparticles and Rayleigh number. The influence of effective dynamic viscosity and thermal conductivity uncertainties of Al_2O_3–water nanofluid has been conducted by Ho et al. [24]. They established their study on free convection heat transfer in a differentially heated square cavity and deduced that heat exchange rate could be enhanced or declined with respect to the base fluid dynamic viscosity. In the recent years, many researches have been focused on free convection heat transfer and fluid flow inside annulus because of their wide applications in various domains such as heat exchangers,

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Nomenclature

B	magnetic flux density
g	gravitational acceleration (m/s^2)
Ha	Hartmann number $\left(=(R_o-R_i)B_x\sqrt{\sigma_f/\mu_f}\right)$
K	thermal conductivity (W/mK)
L	characteristic length, $L = R_o - R_i$
Nu	Nusselt number
Nu_l	local Nusselt number
P	pressure (N/m^2)
Pr	Prandtl number, υ/α
Ra	Rayleigh number, $(g\beta L^3\Delta T/\upsilon\alpha)$
RR	radius ratio, $RR = R_o / R_i$
T	temperature (K)
u, v	components of velocity (m/s)
U, V	dimensionless velocity component
x,y	Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient
φ	nanoparticle volume fraction
ω and Ω	vorticity and dimensionless vorticity
ψ and Ψ	stream function and dimensionless stream function
σ	electrical conductivity
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
θ	dimensionless temperature
γ	angular coordinate
ξ	magnetic field angle

Subscripts

Avg	average
eff	effective
f	fluid
nf	nanofluid
nn	local
S	surface

solar energy collectors, electronic devise cooling, heat storage systems and so on. Abu-nada et al. [25] studied free convection heat transfer enhancement in horizontal concentric annuli filled by nanofluids. They considered four different nanoparticles of Cu, Ag, Al_2O_3 and TiO_2 scattered in base fluid of water and deduced that nanoparticles with higher thermal conductivity enhance the heat transfer rate especially for low Rayleigh numbers. Corcione et al. [26] performed a numerical study of natural convection heat transfer in differentially heated annulus filled by alumina–water nanofluid. They concluded that thermal performance of the nanofluid increases with increasing volume fraction of the nanoparticles up to an optimal loading at which the heat transfer performance has a peak. Mahian and Pop [27] performed an analytical study for the flow and heat transfer characteristics of TiO_2/water nanofluid in a vertical annulus with isoflux walls and under the influence of magnetic field. They found that utilization of TiO_2/water nanofluid reduces the entropy generation but enhances the heat transfer rate in the annulus while an increase in the Hartmann number increases the entropy generation number. Arefmanesha et al. [28] studied free convection heat transport and fluid flow in the annuli of two differentially-heated square ducts filled with TiO_2–water nanofluid. They reported that the average Nusselt number is increased by increasing the gap width between the square ducts and Rayleigh number. Furthermore heat transfer rate was enhanced by increasing volume fraction of the nanoparticles.

The aim of this study is to investigate numerically the effect of a magnetic field on steady free convection heat transfer of Cu–water nanofluid in a cylindrical–triangular annulus which has less been conducted by researchers. Control volume based finite element method (CVFEM) has been employed to deal with such complicated geometry. The effective thermal conductivity and the viscosity of nanofluid have been approximated by the Maxwell-Garnetts (MG) model [29] and the Brinkman model [30] respectively. The study has been carried out for different important governing parameters such as the Hartmann number, Rayleigh number, nanoparticle volume fraction and the annulus radius ratio.

2. Problem formulation

Fig. 1(a) shows schematic diagram of a two dimensional horizontal annulus between an outer circular cylinder with radius of R_o and an inner equilateral triangular cylinder with an unreal inner radius of R_i that are concentrically placed. The radius ratio (RR) is specified as the ratio of the outer circle radius to the radius of the circumscribed circle of the inner equilateral triangle, which is defined as $RR = R_o / R_i$. The inner cylinder is maintained at a constant high temperature of T_h whereas the outer cylinder is kept at a constant low temperature of T_c. The enclosure is filled with a Cu–water nanofluid ($Pr = 6.2$) and it is assumed that the base fluid and the nanoparticles are in thermal equilibrium, incompressible and the thermophysical properties of the fluid are constant (Table 1) except for the density which is estimated by the Boussinesq approximation. A uniform magnetic field with a constant magnitude of B is applied with an orientation angle of ξ. In this study, ξ equals to zero. With these assumptions, the dimensional transport equations are as follows:

Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\sigma_{nf}B^2}{\rho_{nf}}\left(v\sin\xi\cos\xi-u\sin^2\xi\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho_{nf}}g(\rho\beta)_{nf}(T-T_C)+\frac{\sigma_{nf}B^2}{\rho_{nf}}\left(u\sin\xi\cos\xi-v\cos^2\xi\right) \tag{3}$$

Thermal energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where $\alpha_{nf} = k_{nf}/(\rho c_p)_{nf}$.