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Conjugate natural convection in a nanofluid filled partitioned horizontal annulus formed by two isothermal cylinder surfaces under magnetic field

Fatih Selimefendigil [a,*], Hakan F. Öztop [b]

[a] Department of Mechanical Engineering, Celal Bayar University, 45140 Manisa, Turkey
[b] Department of Mechanical Engineering, Technology Faculty, Firat University, 23119 Elazığ, Turkey

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ABSTRACT

Natural convection in a CuO-water nanofluid filled horizontal partitioned annulus formed by two isothermal surfaces under the influence of an inclined magnetic field was numerically investigated. A conductive partition with varying thickness and thermal conductivity was placed within the annulus. Finite element method was utilized to solve the governing equations. The influence of the Rayleigh number (between 10^4 and 10^6), Hartmann number (between 0 and 40), magnetic inclination angle (between 0° and 90°), thermal conductivity of the partition (between 0.06 and 60) and solid volume fraction of the nanoparticle (between 0 and 0.04) on the fluid flow and heat transfer characteristics were studied for various thickness values of the partition. Local and average Nusselt number along the inner surface enhance as the value of the thickness of the partition and Rayleigh number and magnetic inclination angle (up 45°) increase and as the value of Hartmann number decreases. The influence of the thickness of the conductive partition is more pronounced in the conduction dominated regime when Rayleigh number is low and Hartmann number is high. Average heat transfer enhances with thermal conductivity of the partition and this is more effective for a thicker partition. Almost a linearly varying relation exists between the average Nusselt number and solid nanoparticle volume fraction and the slope of the curve is slightly higher for a thick partition.

1. Introduction

Natural convection in the annulus of two horizontal cylinders has been extensively studied in the literature due to its importance in various engineering applications such as heat exchangers, electronic cooling, solar power, thermal energy storage, nuclear reactors and many others. A vast amount of literature study is dedicated to numerical and experimental studies related to natural convection in annular spaces between two cylinders.

Kuehn and Goldstein [1] performed experimental and numerical investigations for the flow field and heat transfer characteristics of a horizontal annulus. They used finite difference method for numerical solution and Mach-Zehnder interferometer was used to experimentally determine the local heat transfer coefficients. Comparisons between the experimental and numerical data shows good agreement. In another study, Kuehn and Goldstein [2] experimentally investigated the effects Rayleigh number and eccentricity on the fluid flow and heat transfer for an annulus bounded by two isothermal cylinder surfaces. The investigated Rayleigh number includes the different flow regimes and eccentricity was found to effect the overall heat transfer coefficient by less than 10%. Garoosi et al. [3] experimentally studied the fluid flow and heat transfer in the annulus of horizontal eccentric cylinders by using optical techniques for a range of Rayleigh number and eccentricity. A numerical study of transient free convection in the annulus of two horizontal isothermal cylinders was performed by Tsui and Tremblay [4] using vorticity-stream function formulation for a range of Grashof numbers and diameter ratio. Cho et al. [5] numerically studied the free convection in the annulus formed by two isothermal cylinder surfaces for concentric and eccentric configurations. Heat transfer and fluid flow characteristics were investigated with respect to a change in the diameter ratio, eccentricity and azimuthal location of the inner cylinder.

In heat transfer applications, nanoparticles are added to the base fluid to control the heat transfer performance [6–21]. The thermal conductivity of the traditional fluids such as water and

* Corresponding author.
E-mail addresses: fatih.selimefendigil@cbu.edu.tr, fthsel@yahoo.com (F. Selimefendigil), hfoztop1@gmail.com (H.F. Öztop).

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Nomenclature

$\mathbf{B}_0$	magnetic field strength
D	hydraulic diameter
Ha	Hartmann number
k	thermal conductivity
K_r	thermal conductivity ratio
n	unit normal vector
Nu_s	local Nusselt number
Nu_m	average Nusselt number
p	pressure
P	non-dimensional pressure
Pr	Prandtl number
R	radius
Ra	Rayleigh number
T	temperature
t	thickness of the partition
u, v	x-y velocity components
U, V	non-dimensional velocity components
x, y	Cartesian coordinates
x, y	non-dimensional Cartesian coordinates

Greek characters

α	thermal diffusivity
β	expansion coefficient
γ	magnetic inclination angle
θ	non-dimensional temperature
ν	kinematic viscosity
ρ	density of the fluid
σ	electrical conductivity
ϕ	solid volume fraction

Subscripts

c	cold
h	hot
i	inner
m	average
nf	nanofluid
np	nano particle
o	outer

ethylene glycol are low and metallic or non-metallic nanoparticles which have higher thermal conductivity has the potential to increase the thermal conductivity of the base fluid with little effect on the pressure drop. The size, type and shape of the particles have influence on the thermal conductivity enhancement of the base fluid and a long lasting stable mixture is needed in various applications. In the application for natural convection in the annulus of the horizontal cylinders, utilization nanofluids is advantageous since heat transfer rate due to natural convection is rather low. Abu-Nada et al. [10] performed computational analysis of natural convection in a horizontal annuli by using water based nanofluid containing different types of nanoparticles. It was observed that for intermediate Rayleigh values, use of nanofluid with low thermal conductivity deteriorates heat transfer and higher values of Rayleigh number and nanoparticle with higher thermal conductivity enhance heat transfer. The natural convection in a semi annulus filled with Cu-water nanofluid was numerically investigated by Soleimani et al. [22] by using control volume based finite element method for a range of Rayleigh number, nanoparticle volume fraction and angle of turn of the enclosure. The use of the nanoparticles was found to be advantageous at low Rayleigh numbers. The use of the nanofluids MHD with nanofluids gives a good possibility to control the convection in some of these systems and it has been studied extensively [23–33]. External magnetic field can be used to control convection and heat transfer application with magnetic field has received some attention recently due to its importance in various engineering applications such as coolers of nuclear reactors, MEMS, purification of molten metals and many others [34]. Sheikholeslami et al. [35] numerically studied the natural convection in a half annulus enclosure filled with Cu-water nanofluid under the influence of magnetic field by using control volume based finite element method for various values of Hartmann number, inclination angle of the enclosure and Rayleigh number. Average heat transfer was found to increase with Rayleigh number and solid volume fraction of the nanoparticles and at low Rayleigh number it increases with Hartmann number. Ashorynejad et al. [36] performed a computational study on natural convection with nanofluids in a horizontal cylindrical annulus with Lattice Boltzmann method under the effect of static radial magnetic field. It was observed that average heat transfer enhances with nanoparticle volume fraction and deteriorates with increasing magnetic field strength. It was also observed that for higher Hartmann number, the primary vortex breaks as the solid volume fraction of the nanoparticle increases.

Obstructions within the enclosures can be used to control the fluid flow and heat transfer characteristics [37–41]. Conjugate heat transfer in a thick walled cavity filled with Cu-water nanofluid was numerically investigated by Mahmoudi et al. [42]. It was observed that the position of the divider has influences on the heat transfer enhancement along with the solid particle volume fraction and Rayleigh numbers. Steady natural convection-conduction in a porous cavity willed with nanofluid and heated by a triangular solid wall was numerically studied by Chamkha and Ismael [43]. Different nanoparticle types were used in water and heat transfer enhancement was found to dependent on the wall thickness and Rayleigh number.

Based on the above literature survey and to the best of our knowledge, natural convection in a horizontal annulus formed by two isothermal cylinder surfaces filled with nanofluid and partitioned with a conductive ring under the effect of inclined magnetic field has never been studied in the literature. This configuration may be encountered in practice in various engineering applications ranging from solar power to nuclear energy or magnetic field, nanoparticle and conductive partition can be used to control the natural convection in annulus. The effects of the Rayleigh number, Hartmann number, inclination angle of the magnetic field, solid volume fraction of the nanoparticles, thickness and thermal conductivity of the conductive partition on the fluid flow and thermal fields are investigated in detail.

2. Mathematical formulation

A schematic description of the problem is shown in Fig. 1. The annulus is formed from two infinitely long horizontal concentric cylinders and it is filled with nanofluid. The radii of the inner and outer cylinders are R_i and R_o with $R_0 = 2R_i$. The inner and outer surfaces of the cylinders are kept at constant temperatures of T_i and T_o with $T_o < T_i$. A conductive partition (a full ring) of thermal conductivity k_s and thickness t is inserted in the annulus. The gap between the cylinder surfaces is $D = R_o - R_i$ and