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Influence of nanoparticles on mixed convection heat transfer in an eccentric horizontal annulus with rotating inner cylinder

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ABSTRACT

Numerical investigation of mixed convection flow and heat transfer with different nanofluids inside an eccentric horizontal annulus is presented. The nanofluids include Cu, TiO_2 and Al_2O_3 nanoparticles with water as a base fluid. The inner and outer cylinders are kept at different constant temperatures with the inner at a higher magnitude than the outer. Moreover, the inner cylinder rotates to create the forced convection effect. Different scenarios are explored to clarify the effects of Richardson number, eccentricity ratio, and solid volume fraction with ranges of 0.01 (forced convection) $\leq$ Ri $\leq$ 100 (natural convection), $0 \leq \varepsilon \leq 0.9$, and $0.01 \leq \lambda \leq 0.05$, respectively. Results are accomplished with Grashof number, and radius ratio, equal to 10^4 and 2, respectively. The generated results include the average Nusselt number, streamlines, and isotherms. The numerical work is carried out using an in-house CFD code written in FORTRAN. Results are discussed and are found to be in good approval with preceding works. It is found that the effect of nanoparticles on the heat transfer enhancement is more pronounced at mixed convection (Ri = 1) and natural convection regions (Ri >1), however at forced convection region (Ri $\leq$ 0.1) the nanoparticles addition has an opposite effect.

1. Introduction

Recently, convection heat transfer between two eccentric and concentric cylinders has been the topic of many theoretical and experimental studies. This is due to its great importance in many engineering applications, such as heat exchangers, journal bearing, electrical motors and generators, thermal storage systems and cooling of electronic components. Many studies have been performed for the classical natural convection heat transfer problems in a horizontal annulus [1–8]; these studies were only for pure fluid. Yoo [9–11] studied the effect of Prandtl number on the natural convection within horizontal cylindrical annulus with different solutions methods. Also, the solution methodology of natural convection within concentric and eccentric annulus for both laminar and turbulent flow was performed [12–16]. In addition, the natural convection in horizontal cylindrical annulus employing porous media is studied [17–22] due to its importance in many industrial applications such as solar collector and energy storage systems.

Extraordinary considerable efforts to augment the rate of heat transfer in different ways have been executed by several investigations. As a pioneering idea, nanofluid has been announced [23–26], accordingly the natural convection in horizontal annulus is enhanced by the nanoparticles addition [27–30]. Abu-Nada et al. [31] studied the effect of nanoparticles addition on the natural convection of a nanofluid in a concentric annulus taking into account variable viscosity and variable thermal conductivity. Also, Matin and Pop [32] studied numerically the natural convection flow and heat transfer of Copper (Cu)–water nanofluid inside an eccentric horizontal annulus, they investigated the effects of eccentricity, radii ratio, nanoparticles volume fraction, Rayleigh number and Prandtl number on the average Nusselt number. It was found that the eccentricity has a significant effect on the heat transfer rate.

Mixed convection heat transfer in horizontal cylindrical annulus has less attention, Al-Amiri et al. [33] and Teamah [34] investigated numerically the double-diffusive mixed convection within a two-dimensional, horizontal annulus, with the rotation of the outer cylinder, they found that the heat transfer is influenced by Richardson number as well as Lewis number, Prandtl number, and the buoyancy ratio. Mozayyeni and Rahimi [35] performed numerical solution for mixed convection of fluid in the fully developed region in a horizontal concentric cylindrical annulus with different uniform wall temperatures, in addition, the outer cylinder is rotated in anticlockwise direction, and the fluid inside the annulus is subjected to a uniform magnetic field. Char et al. [36] performed numerical computations for turbulent mixed convection of air in horizontal concentric annulus between cooled outer cylinder

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Nomenclature

b	Annulus gab width,($r_o - r_i$), m.
C_P	Specific heat at constant pressure, J/kg K.
e	Eccentricity, m.
g	Acceleration of gravity, m/s^2
Gr	Thermal Grashof number.
k	Thermal conductivity, W/m K.
Nu	Average Nusselt number.
Nu_ϕ	Local Nusselt number.
p	Pressure, N/ m^2.
P	Dimensionless pressure.
Pe	Péclet number.
Pr	Prandtl number.
r	Radial coordinate.
r_i, r_o	Inner and outer radii respectively, m.
R	Dimensionless radial coordinates.
Ra	Thermal Rayleigh number.
Ri	Richardson number.
Re	Rotational Reynolds number.
Rr	Radius ratio.
T	Local temperature, K.
T_c, T_h	Temperatures at outer and inner radii respectively, K.
ΔT	Temperature difference, ($T_h - T_c$), K.
u	Radial velocity in transform rectangular domain, m/s.
v	Tangential velocity in transform rectangular domain, m/s.
v_r	Velocity in r-direction, m/s.
v_ϕ	Velocity in ϕ-direction, m/s.
Greek symbols	
α	Thermal diffusivity, m^2/s.
β	Coefficient of thermal expansion, K^{-1}.
ε	Eccentricity ratio.
ϕ	Angular coordinate.
λ	Solid volume fraction.
ν	Kinematic viscosity, m^2/s.
ω	Angular velocity, rad/s.
ρ	Density, kg/m^3.
θ	Dimensionless temperature.
Subscript	
f	Fluid.
nf	Nanofluid
s	Solid.

and heated, rotating inner cylinder at low Reynolds number. The results showed that the rotation has caused a significant reduction in the mean heat transfer. Khanafer and Chamkha [37] investigated mixed convection in horizontal annulus filled with a uniform fluid-saturated porous medium in the presence of internal heat generation. The inner cylinder is heated while the outer cylinder is cooled. The obtained results depicted that, Richardson number plays a significant role in the heat transfer characterization within the annulus.

Nevertheless, the studies of mixed convection [33–37] have been limited to the concentric annulus, without nanoparticles addition.

Cao et al. [38] proposed a decent methodology in simulating the complex convection heat transfer phenomena, they proposed a numerical approach for dealing with irregular geometries in dissipative particle dynamics system and by which the application of dissipative particle dynamics can be extended to mimic hydrodynamics in arbitrarily complex geometries, good agreement between their proposed methodology and both the finite volume solutions and the experimental data as well as the lattice Boltzmann method.

However, to the knowledge of the authors, it is the first time which flow in an annulus has been considered with employing mixed convection heat transfer utilizing nanofluid. The eccentricity effect on the mixed convection heat transfer in an annulus utilizing nanofluid gives a value to this study.

2. Scope and objective

The scope of the present work is focused on studying the effects of nanoparticles type (thermal properties effect) and volume fraction, on the heat transfer in an eccentric annulus subjected to mixed convection heat transfer. The numerical work is conducted after laborious affirmation and validation procedures, which demonstrated that the code solves the governing equations with insignificant numerical and modeling errors. The main objective of the present work is to establish the superior nanoparticle type from the commonly used nanoparticles (Cu, TiO_2, and Al_2O_3) to enhance the heat transfer within the eccentric annulus. The methodology followed to achieve these objectives, via numerical analysis using an in-house CFD code written in FORTRAN, were greatly built on a comprehensive, practical understanding of the verification and validation processes mandatory for CFD analysis.

3. Mathematical model and computational approach

The system under consideration is shown in Fig. 1 in both dimensional and dimensionless forms. The dimensionless form, include both polar (R,ϕ) coordinates and transform rectangular (ζ, η) coordinates. The steady-state two-dimensional mixed convection of a different nanofluid in annuli of eccentric horizontal cylinders is considered. The outer cylinder is kept cooled at temperature T_c while the inner cylinder is kept at hot temperature T_h. The eccentricity is considered below the center of the outer cylinder (downward). The temperature gradient generates the natural convection due to the buoyancy effect that signified the Grashof number while the inner cylinder rotation generates the forced convection that signified the Reynolds number. Via the inner cylinder rotation, the Richardson number ($Ri = Gr/Re^2$) is created (the Grashof number is fixed at 10^4). The following assumptions are introduced:

- Thermal equilibrium between the base fluid and nanoparticles
- Newtonian and incompressible laminar flow

Constant thermo-physical properties are considered for the nanofluid while the Boussinesq approximation is used for the density variation in the buoyancy forces.

$$\rho = \rho_o[1 - \beta\,(T - T_c)]. \tag{1}$$

Where β is the coefficient of thermal expansion such that:

$$\beta = -\frac{1}{\rho_o}\left(\frac{\partial \rho}{\partial T}\right)_{P=C}. \tag{2}$$

The governing equations for the problem under consideration are continuity, momentum and thermal energy in two dimensions steady state. For generalization, the governing equations should be in dimensionless form by the following formulations:

$$V_r = \frac{v_r}{\omega ri}, V_\phi = \frac{v_\phi}{\omega ri}, R = \frac{r}{b}, \theta = \left(\frac{T - T_c}{T_h - T_c}\right), P = \frac{p}{\rho_{nf}(\omega ri)^2},$$
$$Rr = \frac{r_o}{r_i}, \ \varepsilon = \frac{e}{b}, \ \mathrm{Re} = \frac{\omega\, r_i\, b}{\nu_f}, \mathrm{Pr} = \frac{\nu_f}{\alpha_f}, Ri = \frac{Gr}{\mathrm{Re}^2},$$
$$Pe = \mathrm{Re}\ \mathrm{Pr}\ , U = \frac{u}{\omega ri}\ , V = \frac{v}{\omega ri}. \tag{3}$$