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Natural convection heat transfer under constant heat flux wall in a nanofluid filled annulus enclosure

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Abstract In this investigation, the Control Volume based Finite Element Method (CVFEM) is used to simulate the natural convection heat transfer of Cu–water nanofluid in an annulus enclosure. The Maxwell–Garnetts (MG) and Brinkman models are also employed to estimate the effect of thermal conductivity and viscosity of nanofluid. The governing parameters are the Rayleigh number, nanoparticle volume fraction and the aspect ratio (ratio of the outer radius to the inner one). Results are presented in the form of isotherms, streamlines, local and average Nusselt numbers. The results indicate that increment of the aspect ratio increases the value of average Nusselt number. Moreover, the angle of turn for the boundary condition of the inner cylinder significantly affects the values of local Nusselt number, average Nusselt number, streamlines and isotherms.

1. Introduction

Study of natural convection heat transfer in the annulus between two horizontal concentric cylinders has been the topic of interest for researchers because of the wide applications in engineering and industry such as nuclear reactor design, aircraft cabin insulation, cooling system in electronic components, solar collector–receiver, thermal storage system and vapor condenser for water distillation and food process [1,2]. The literature survey shows that there is numerous works on both experimental and numerical investigation natural convection heat transfer between two concentric circular cylinders. Kuehn and Goldstein [3] conducted an experimental and theoretical study of natural convection in concentric and eccentric horizontal cylindrical annuli. Kuehn et al. [4,5] presented experimental and numerical studies of steady-state natural convection heat transfer in horizontal concentric annuli, in which the effects of Rayleigh and Prandtl numbers and aspect ratio were parametrically explored and correlating equations, were proposed as well. The numerical and experimental analysis of natural convection from a horizontal cylinder enclosed in a rectangular cavity has been performed by Cesini et al. [6]. They investigated the effect of the cavity aspect ratio and the Rayleigh number on the isotherms and Nusselt number. Their

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Nomenclature

C_p	specific heat at constant pressure
Gr_f	Grashof number
Nu_{local}	local Nusselt number
Nu_{ave}	average Nusselt number
Pr	Prandtl number ($=\upsilon/\alpha$)
T	fluid temperature
u, v	velocity components in the x-direction and y-direction
U, V	dimensionless velocity components in the X-direction and Y-direction
x, y	space coordinates
X, Y	dimensionless space coordinates
r	non-dimensional radial distance
rr	aspect ratio
k	thermal conductivity
L	gap between inner and outer boundary of the enclosure $L = r_{out} - r_{in}$
$\vec{g}$	gravitational acceleration vector
q	heat flux
Ra	Rayleigh number ($= g\beta q''(r_{out} - r_{in})^4/k_f\alpha v$)

Greek symbols

ζ	angle measured from the lower right plane
γ	angle of turn for boundary condition
α	thermal diffusivity
ϕ	volume fraction
μ	dynamic viscosity
υ	kinematic viscosity
ψ & Ψ	stream function & dimensionless stream function
Θ	dimensionless temperature
ρ	fluid density
β	thermal expansion coefficient
ε	dimensionless length of the heat source

Subscripts

c	cold
h	hot
ave	average
nf	nanofluid
f	base fluid
s	solid particles
in	inner
out	outer

results show that with increasing Rayleigh number, the average heat transfer coefficients increases. Bararnia et al. [7] studied the natural convection around a horizontal elliptic cylinder inside a square enclosure using LBM. They found that streamlines, isotherms and the number, size and formation of the cells strongly depend on the Rayleigh number and the position of inner cylinder. The forced and free convection for thermally developing and fully developed laminar airflow inside horizontal concentric annuli has been investigated experimentally by Mohammed et al. [8]. This investigation revealed that the Nusselt number is considerably greater for developing flow than the corresponding values for fully developed flow over a significant portion of the annulus. Ghaddar [9] reported the numerical results of natural convection from a uniformly heated horizontal cylinder placed in a large air-filled rectangular enclosure. He observed that flow and thermal behavior depend on heat fluxes impose on the inner cylinder within the isothermal enclosure. Hussain and Hussein [10] investigated the natural convection phenomena in a uniformly heated circular cylinder at different vertical locations immersed in a square enclosure filled with air numerically. Their result showed that the average and local Nusselt number values increase with different upward and downward locations of the inner cylinder with increasing Rayleigh number. Haldar [11] reported numerical study of combined convection through a horizontal concentric annulus using a combination of vorticity–stream function and primitive variables formulations. It was found that with increasing axial distance, the entry effect diminishes, while the buoyancy becomes stronger. Natural convection in cavities with constant flux heating at the bottom wall and isothermal cooling from the sidewalls is investigated numerically by Sharif and Mohammad [12]. They analyzed the effects aspect ratio, inclination angles, and heat source length on the convection and heat transfer process in the cavity. Their results showed that the average Nusselt number and maximum temperature change mildly with aspect ratio as well as with heat source length. Cheikh et al. [13] studied the natural convection cooling of a localized heated plate embedded symmetrically at the bottom of an air-filled square enclosure. Khanafer et al. [14] firstly conducted a numerical investigation on the heat transfer enhancement due to adding nano-particles in a differentially heated enclosure. They found that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. Natural convection heat transfer in an inclined enclosure filled with a water–CuO nanofluid is investigated numerically by Ghasemi and Aminossadati [15]. They found that the heat transfer rate is maximized at a specific inclination angle depending on Rayleigh number and solid volume fraction. Aminossadati and Ghasemi [16] presented the results of a numerical study on natural convection in a partially heated enclosure from below and filled with different types of nanofluids. Their results showed that the increase of solid volume fraction of nanoparticles causes the heat source maximum temperature to decrease particularly at low Rayleigh numbers. Nabavitabatabayi et al. [17] presented a numerical study on the heat transfer performance in an enclosure including nanofluids with a localized heat source. They observed that by adding nanoparticles to base liquid causes the maximum temperature decrease on account of the irregular motion of nanofluids and, more importantly, the higher energy transport rate inside the fluid. Abu-Nada et al. [18] investigated natural convection heat transfer enhancement in horizontal concentric annuli field by nanofluid. They found that for low Rayleigh numbers, nanoparticles with higher thermal conductivity cause more enhancement in heat transfer. Bararnia et al. [19] studied the natural convection in a