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Natural convection of a nanofluid inside a vertical circular enclosure exposed to a non-uniform heat flux☆

Meisam Habibi Matin *, Shadi Vaziri

CFD Research Centre, Department of Mechanical Engineering, Kermanshah University of Technology, Azadegan Sq., 67178-63766 Kermanshah, Iran

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ABSTRACT

In the present study natural convection of Al_2O_3-water nanofluid inside a vertical circular enclosure is investigated. The enclosure is exposed to heat flux with a non-uniform distribution from the bottom. The objective is finding the heat flux distribution for which the heat transfer coefficient is optimum at different values of the governing parameters. For examining the effect of heat flux distribution on thermal transport phenomenon, 9 various flux distributions are considered as cases 1 to 9. The bottom side of the enclosure is divided to six annular strips each of which receives a portion of the total heat i.e., the flux applied on each strip is different. The side wall is kept at constant temperature and the top wall is assumed to be adiabatic. A numerical finite volume scheme is employed to solve non-dimensional conservative equations in cylindrical coordinates. In addition to the heat flux distribution, the effects of Rayleigh number (10^4<Ra<10^6), nanoparticles volume fraction (φ<0.08) and aspect ratio (Γ = 0.5, 1 and 1.5) on isotherms and Nusselt number are analyzed. It is observed that there are physical conditions for which the heat transfer characteristic is optimized.

1. Introduction

Natural convection which occurs spontaneously due to buoyancy effects has received a great deal of attentions ever since from researchers on account of its significance in natural and technological phenomena. Free convection in enclosures plays an important role in a numerous practical applications and industrial devices such as boilers, fluid storage vessels, fuel tanks, chemical reactors, crystal growth systems, to name a few. Several studies have focused on the convective heat transfer inside vertical circular enclosures as a basic geometry. The primary studies in this field were devoted to the most known configuration as Rayleigh- Benard configuration in vertical circular cylinder heated from bellow [1–3]. Notwithstanding many attempts that are made in two dimensional modeling of the convective heat transfer inside the enclosures Kurian et al. [4] exhibited that flow visualization of free convection inside circular cylinders reveals complex three-dimensional patterns. Considering an inclination angle for the cylinder, they restricted their study to Rayleigh numbers less than 3.1×10^4 to ensure that the flow is laminar. There is no unanimous report about the critical Rayleigh number in circular cylinders since there is a paucity of related works with the identical configuration and boundary conditions. Searching through the open literature one can come to the conclusion that the critical Rayleigh number depends on geometrical parameters such as inclination angle and aspect ratio (height/diameter) of the cylinder [5–9]. In one experimental study by Heslot et al. [8] on cylinders with aspect ratio of unity and adiabatic sidewall, turbulent patterns were revealed at Ra = 10^7. It should be noted that in cylinders with the aspect ratio greater than unity the transition to turbulent takes place at higher Rayleigh number because in cylinders of diameter comparable to the height or lower, the onset of convection is delayed due to viscous damping occurred by the surrounding surface. This assertion was proved by He et al. [10]. They also showed that the Nusselt number increases with the increase of Ra or decrease of aspect ratio. Two dimensional laminar natural convection in a cylindrical enclosure laterally heated was analyzed by Lemembre and Petit [11]. Their work was developed by Ma et al. [12] that implemented a numerical approach to simulate the three dimensional unsteady natural convection in a laterally heated cylindrical enclosure.

Since the energy saving is an indisputable aspect of having progressive economy and standard environment, optimal design of thermal systems is something inevitable that engineers are looking for. Optimal conditions are achievable just when these systems work efficiently. For both cooling and heating purposes we are required to increase the heat transfer coefficient to have the minimum energy loss and hence maximum efficiency in such systems. Knowing this as a fact has motivated the researchers to seek the ways of enhancing the heat transfer rate in the thermal systems including enclosures as one of the most important ones. Enormous attempts have been made towards this purpose from alternation of geometry to replacing new working fluids in the enclosures.

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* Corresponding author.
E-mail address: habibimeisam@yahoo.com (M. Habibi Matin).

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Nomenclature

g	gravity acceleration
h	heat transfer coefficient
H	height of cylinder
k	thermal conductivity
Nu	Nusselt number
Nu_L	local Nusselt number
p	pressure field
q''	heat flux
Pr	Prandtl number
r	radial coordinate
R	radius of the cylinder
Ra	Rayleigh number
T	temperature
T_c	temperature of the curved wall
T_w	temperature of the bottom wall
u	radial velocity
v	tangential velocity
w	vertical velocity
z	vertical coordinate

Greek Symbols

Γ	aspect ratio of the cylinder
Θ	dimensionless temperature
θ	angular coordinate
α	thermal diffusivity
ρ	density
ν	kinematic viscosity
σ	angular position
φ	nanoparticle volume fraction
β	thermal expansion coefficient

Subscripts

ave	average
f	base fluid
nf	nanofluid
s	solid particle

In the last two decades, nanofluids have been introduced as a new way of increasing the efficiency of the systems of convective transport. Conventional fluids, such as water, ethylene glycol mixture and some types of oil have low heat transfer coefficient that might be pertained to the low thermal conductivity of these fluids. Liquids as the working fluid in the majority of thermal systems suffer a low thermal conductivity that limits the heat transfer rate in such systems. However, the ever-increasing trend of miniaturizing of electronic devices necessitates further heat transfer improvements from an energy saving viewpoint. For the first time Choi [13] enjoyed the innovative idea of adding particles in nanoscale to the pure fluid in order to introduce advanced mixtures with substantially higher thermal conductivity. The resulting mixture of the base fluid and nanoparticles having unique physical and chemical properties is referred to as nanofluid. It is expected that the presence of the nanoparticles in the nanofluid increases the thermal conductivity and therefore substantially enhances the heat transfer characteristics of the nanofluid. Eastman et al. [14] and Xie et al. [15] showed that higher thermal conductivity can be achieved in thermal systems using nanofluids. Choi et al. [16] affirmed that the addition of 1 % by volume of nanoparticles to conventional fluids increases the thermal conductivity of the fluid up to approximately two times.

Since the idea of nanofluid was introduced, a scarce number of works have been devoted to the natural convection in cylindrical enclosures and by far the most researches have focused on rectangular and annular cavities [17–19]. Sheikholeslami and Ellahi [20] numerically investigated the influence of Ra number and volume fraction of nanofluid on Nusselt number for a cubic cavity under the impact of a magnetic field. They concluded that the Nusselt number has an increasing trend versus Rayleigh number and nanofluid volume fraction irrespective of the presence of the magnetic field. Experimental studies were conducted by Moradi et al. [21,22] to evaluate the effects of Rayleigh number and nanoparticles volume fraction on the heat transfer characteristics in a circular enclosure with a constant heat flux on the bottom wall. Nanofluids TiO_2-water and Al_2O_3-water were examined. They observed that adding nanoparticles to water has a negligible or even adverse influence on natural convection heat transfer. They also found that at low Ra the heat transfer enhancement is more probable than at high Ra. As of late, Rashidi et al. [23] studied buoyancy driven convection in a square cavity filled with Al_2O_3-water nanofluid to realize the effect of bottom wall heat flux distribution on the heat transfer rate. They could find the optimal conditions for Nusselt number in terms of Ra number, nanofluid volume fraction and heating load.

In this study three dimensional numerical simulation of natural convection of Al_2O_3-water nanofluid inside a vertical circular enclosure is focused. The enclosure is exposed to heat flux with a non-uniform distribution from bellow. The side wall is kept at constant temperature and the top wall is adiabatic. The objective is finding the heat flux distribution for which the heat transfer coefficient is optimum at various values of Rayleigh number, aspect ratio and nanoparticles volume fraction. For examining the effect of heat flux distribution on thermal transport phenomenon, 9 various flux distributions are considered as cases 1 to 9. The bottom wall of the enclosure is divided to six annular strips each of which receives a portion of the total heat. A numerical finite volume scheme is employed to solve non-dimensional conservative equations in cylindrical coordinates.

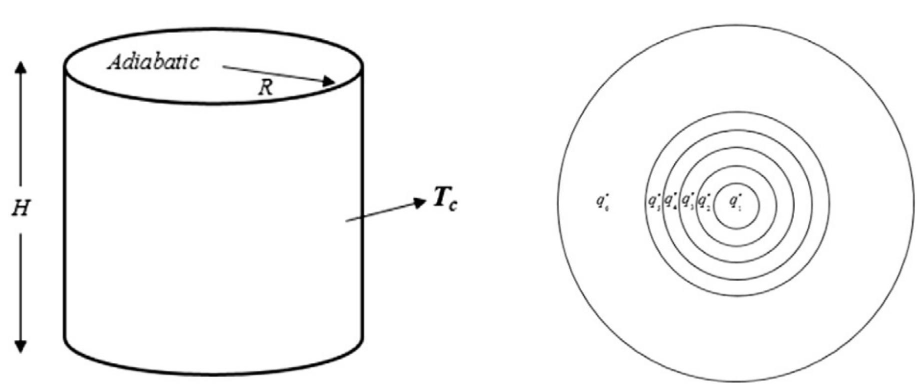

Fig. 1. Schematic of (a) the physical model and (b) flux distribution on the bottom surface.