International Communications in Heat and Mass Transfer 90 (2018) 44–55

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

A comparison study of mixed convection heat transfer of turbulent nanofluid flow in a three-dimensional lid-driven enclosure with a clockwise versus an anticlockwise rotating cylinder

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ARTICLE INFO

Keywords:
Mixed convection
Rotating cylinder
Lid-driven cavity
Turbulent flow
URANS

ABSTRACT

A turbulent 3D mixed convective flow of pure water, H_2O, and nanofluid, SiO_2-H_2O, inside a differentially heated moving wall enclosure containing an insulated rotating cylinder over a range of rotational speeds, $-5 \le \Omega \le 5$, Reynolds numbers, 5000 and 10,000, and constant Grashof number, is numerically investigated. A cooled lid-driven top wall and a heated bottom wall are the only thermally uninsulated walls in this domain. A standard k-ε for the Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach is applied to the turbulence calculation. Nusselt number, mean velocity profile, streamline, isothermal and isosurface temperatures are derived and presented in this paper to gain a better understanding of the effects of clockwise and anti-clockwise rotating cylinder directions on the heat transfer and flow patterns. Interesting changes in flow structure and heat transfer have been analysed for all rotational speeds and fluid types at both Reynolds number values. Nonlinear increases in Nusselt number have been observed by using nanofluid instead of pure water. The wall shear stress and turbulent kinetic energy profiles are found to be influenced by changing the Reynolds number and rotational speed and direction. Furthermore, incremental heat transfer rates at the walls can be achieved by increasing the cylinder rotation speeds, but these increases have weaker influences on the top wall than on the bottom wall.

1. Introduction

The mixed convective flow of moving wall cavity is produced as a result of both natural and forced convection. Since heat convection can be represented in many cavity configurations, it has many industrial and engineering applications such as electronic cooling, lubrication technologies, oil extraction, solar collectors, food processing [1–8], many researchers have investigated various free or mixed convection problems. Involving some additional passive objects within the enclosure to enhance the heat transfer ratio has become popular over the years. Sun, et al. [9] added a triangular fin to control the heat transfer of the mixed convection case.

Inserting a circular body to enhance the heat transfer of a lid-driven cavity was investigated by Oztop, et al. [10]. Appending a heated triangular block at the centre the top moving wall square enclosure has an impact on the heat transfer coefficient [11]. Studying the effects of both inserting an isothermal square object and using a nanofluid inside a lid-driven square enclosure on the heat transfer ratio was undertaken by Mehmood, et al. [12]. Nonetheless, it may be noticed that neither the 3D domain nor turbulent flow condition has been used in the above references.

Moreover, some studies of mixed convection have been completed by introducing one cylinder or more within the enclosures to control and increase the heat transfer ratio. A 2D laminar mixed convection heat transfer of nanofluid within a moving wall square enclosure containing a rotating cylinder was considered by Mirzakhanlari, et al. [13] to study the impacts of the Richardson number and rotational speed. It was demonstrated that increasing either the Richardson number or the nanofluid speed causes an enhancement in heat transfer ratio, while increasing the rotational speed of the cylinder has a negative effect on the heat transfer ratio. A 2D free convection study of a laminar power-law fluid within a square cavity containing a heated cylinder was completed by Shyam, et al. [14], which concentrated on the effects of changing the cylinder location along the vertical central line for different dimensionless parameters. It was realised that the heat transfer ratio and streamline and isotherm contours can be affected by changing the Grashof and Prandtl number or cylinder location. A study of 2D laminar natural convection of air within a cold-walled square enclosure containing a stationary sinusoidal cylinder was undertaken by Nabavizadeh, et al. [15] to evaluate the influences of different angles,

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https://doi.org/10.1016/j.icheatmasstransfer.2017.10.016

Available online 24 November 2017
0735-1933/

Nomenclature

CFL	Courant–Friedrichs–Lewy number
D	width of the cavity on z-axis (m)
d	cylinder diameter (m)
FVM	finite volume method
Gr	Grashof number ($g\beta_m \Delta T W^3/\nu_m{}^2$)
h	convective heat transfer coefficient (W/m^2K)
k	turbulent kinetic energy (m^2/s^2)
L	width of the cavity on x-axis (m)
Nu	Nusselt number
Pr	Prandtl number (ν_m/α_m)
Re	Reynolds number ($U_{0,m}W/\nu_m$)
Ri	Richardson number (Gr/Re^2)
$\bar{S}_{ij}$	large-scale strain rate tensor for grid-filter
T	temperature of the fluid (K)
t	time
u	velocity component at x-direction (m/s)
U	dimensionless velocity component at x-direction
U_0	lid velocity (m/s)
v	velocity component at y-direction (m/s)
V	dimensionless velocity component at y-direction
W	dimensionless velocity component at z-direction
x	distance along the x-coordinate
X	distance along the non-dimensional x-coordinate (x/L)
Y	distance along the non-dimensional y-coordinate (y/H)
Z	distance along the non-dimensional z-coordinate (z/D)

Greek symbols

α	thermal diffusivity of the fluid (m^2/s)
β	volumetric coefficient of thermal expansion (1/K)
μ	dynamic viscosity of the fluid (Pa/s)
ν	kinematic viscosity of the fluid (m^2/s)
ρ	density of the fluid (kg/m^3)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
ω	rotational speed (rad/s)
Ω	dimensionless rotational speed

Subscripts

av	average value
b	buoyancy
C	value of cold temperature
H	value of hot temperature
rms	root mean square
sgs	sub-grid scale
t	turbulent

amplitudes and number of cylinder undulations. It was observed that changing cylinder parameters can affect the heat transfer and fluid patterns. Three-dimensional free convection of laminar flow within an enclosure containing a cylinder was simulated by Souayeh, et al. [16] in order to understand the impact of inclination angles of the cylinder at different Rayleigh numbers on the fluid patterns and heat transfer ratio. It was noted briefly that a significant effect was discovered regarding the heat transfer ratio, especially when the Rayleigh number is 10^6 and inclination angle is 90°. Limited research has been completed into mixed convection turbulent flow within lid-driven enclosures by utilizing an unsteady approach such as URANS (Unsteady Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation). Combined convection heat and mass transfer of water within a lid-driven cavity was studied by Kareem, et al. [1] to analyse the 3D flow structure and heat transfer by involving unsteady RANS and LES methods at various Reynolds numbers. The results have shown the ability of both methods to deal with the vortices of the turbulent flow. Nevertheless, secondary eddies were dealt with more comprehensively by utilizing the LES method. In addition, it was concluded that a remarkable effect on the heat transfer ratio and fluid patterns can be observed when the Reynolds number increases. Two different turbulent methods are used by Kareem and Gao [17] to study a combined mixed convection of different nanofluid types within a 3D moving sidewalls enclosure. It was demonstrated that heat transfer and flow pattern can be influenced by adding nanoparticles to the pure fluid, and that the influence of the ratio could be changed by using different types, diameters and concentrations of nanoparticles. A clear difference in heat transfer rate has also been noticed by utilizing different turbulence methods.

Studies into various nanofluid types within cavities have been described by a number of researchers because of its considerable effect on heat transfer enhancement. Investigation of free and combined convective heat transfer of a differentially heated circular cylinders within an adiabatic cavity containing nanofluid was studied by Garoosi and Hoseininejad [18]. The influences of nanofluid thermophysical properties and the number of cold cylinders that the cavity contained and their location and rotational directions are considered at different Rayleigh and Richardson numbers. It has been found that increasing or decreasing heat transfer rate strongly depends on these parameters. Kareem, et al. [19] studied a laminar mixed convection of heat and mass transfer in a 2D trapezoidal moving wall enclosure that is filled with different types of nanofluid in a numerical manner. The authors aimed at an understanding of the effects of nanofluid type, nanoparticle diameter, inclined sidewall angle, aspect ratio, flow direction and Richardson number on the heat transfer ratio and flow distribution. It was concluded that SiO_2-H_2O showed the highest Nusselt number and aiding flow direction provides for a higher heat transfer ratio. In addition, it has been found that increasing the nanoparticle concentration and aspect ratio leads to an increase in the heat transfer coefficient, unlike when the nanoparticle diameter and inclination angle are increased.

It can be summarized from the current literature review that a study considering the effects of three-dimensional rotating cylinders in terms of their speeds and directions (clockwise and anticlockwise) within a top lid-driven closed cavity on turbulent nanofluid flow, and involving the unsteady RANS method, is unprecedented, and this consequently forms the main objectives of this paper.

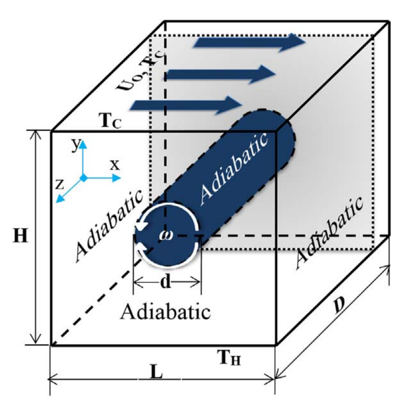

Fig. 1. Schematic of the analysed configuration.