International Communications in Heat and Mass Transfer 95 (2018) 197–209

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Effect of rotating solid cylinder on entropy generation and convective heat transfer in a wavy porous cavity heated from below

Ammar I. Alsabery[a,b,*], Tahar Tayebi[c,d], Ali J. Chamkha[e,f], Ishak Hashim[b]

[a] *Refrigeration & Air-conditioning Technical Engineering Department, College of Technical Engineering, The Islamic University, Najaf, Iraq*
[b] *Centre for Modelling & Data Science, Faculty of Science & Technology, Universiti Kebangsaan Malaysia, Bangi 43600 UKM, Selangor, Malaysia*
[c] *Faculty of Sciences and Technology, Mohamed El Bachir El Ibrahimi University, Bordj Bou Arreridj, El-Anasser, Algeria*
[d] *Energy Physics Laboratory, Department of Physics, Faculty of Science, Mentouri Brothers Constantine1 University, Constantine, Algeria*
[e] *Department of Mechanical Engineering, Prince Sultan Endowment for Energy and the Environment, Prince Mohammad Bin Fahd University, Al-Khobar 31952, Saudi Arabia*
[f] *RAK Research and Innovation Center, American University of Ras Al Khaimah, P.O. Box 10021, Ras Al Khaimah, United Arab Emirates*

ARTICLE INFO

Keywords:
Entropy generation
Heat transfer
Wavy porous cavity
Rotating cylinder
Heat source

ABSTRACT

The aim of the present study is to analyze the entropy generation and convective heat transfer in a bottom-heated wavy porous cavity containing a solid rotating cylinder. An isothermal heater of length h is placed on the bottom wall of the cavity, while both the left and right vertical wavy walls are maintained at a constant cold temperature T_c. The remainder parts of the bottom wall and the top wall are kept adiabatic. The Forchheimer-Brinkman-extended Darcy model is assumed to hold. The dimensionless governing equations subject to the selective boundary conditions are solved numerically using the Galerkin weighted residual finite element method. The governing parameters of this study are the Rayleigh number ($Ra = 10^5$ and 10^6), angular rotational velocity ($-1000 \leq \Omega \leq 1000$), Darcy number ($10^{-6} \leq Da \leq 10^{-2}$), number of oscillations ($1 \leq N \leq 4$) and porosity of the medium ($0.2 \leq \varepsilon \leq 0.8$). The developed computational code is validated comprehensively using the grid independence test and numerical data of other authors. The obtained results reveal that the flow control can be accomplished by the angular rotational velocity or direction of the cylinder rotation, which have important design implications in practical applications. In addition, an augmenting in the porosity of the medium causes an increase in heat transfer from the wall to the fluid and therefore an increase in the convective flow and consequently a decrease in the Bejan number.

1. Introduction

Convection flow and heat transfer in porous medium has been a subject of great interest in the past three decades due to the wide range of industrial applications, such as geothermal reservoirs, matrix heat exchangers, float glass production, flow and heat transfer in solar ponds, air conditioning in rooms, optimization of solidification processes of metals and alloys, waste nuclear processing, dissemination control of chemical waste and pollutants, electronic packages, grain storage systems and many others [1,2]. Natural and mixed convection and heat transfer in closed cavities with different shapes occupies a large part of the heat transfer literature. Square, rectangle, triangle, cylindrical, elliptical and spherical geometries have been studied in many researches. Complex geometries cover different types of geometrical configurations, namely wavy wall cavities, concave and convex curved wall cavities, etc. A very recent comprehensive literature survey concerning convection heat transfer in wavy porous cavities is given by Shenoy et al. [3]. The authors of this book provided an excellent background in the field of natural convection and heat transfer in wavy cavities filled with viscous fluids, porous media, and nanofluids.

Studies dealing with convective heat transfer problems within complex geometries have received a considerable attention in the literature because their wide applications in many engineering problems like solar collectors, micro-electronic devices, electrical and nuclear components, etc. Kumar [4] analyzed numerically free convection heat transfer and fluid flow inside a vertical wavy enclosure filled with a porous media. He reported that the heat transfer was very sensitive to the Rayleigh number, wave amplitude, wave phase, and number of waves in the vertical dimension of the cavity. Das and Mahmud [5] have studied natural convection inside a wavy walled enclosure consisting of two isothermal horizontal wavy walls and two straight adiabatic vertical walls. Their results illustrated that the amplitude and the

* Corresponding author at: Refrigeration & Air-conditioning Technical Engineering Department, College of Technical Engineering, The Islamic University, Najaf, Iraq.
E-mail address: ammar_e_2011@yahoo.com (A.I. Alsabery).

https://doi.org/10.1016/j.icheatmasstransfer.2018.05.003

Nomenclature

A	amplitude
Da	Darcy number
h	length of the heat source
H	dimensionless length of the heat source, $H = h/L$
k	thermal conductivity
K_r	solid cylinder to fluid thermal conductivity ratio, $K_r = k_s/k_f$
L	width and height of the square cavity
N	number of oscillations
N_μ	irreversibility distribution ratio
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
S_{gen}	entropy generation rate
S_{GEN}	dimensionless entropy generation rate
S_θ	dimensionless entropy generation due to heat transfer irreversibility
S_Ψ	dimensionless entropy generation nanofluid friction irreversibility
T	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 & X, Y	space coordinates & dimensionless space coordinates

Greek symbols

α	thermal diffusivity
ε	porosity of the medium
θ	dimensionless temperature
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ω & Ω	angular rotational velocity, dimensionless angular rotational velocity

Subscript

b	bottom
c	cold
f	base fluid
h	hot
i	interface
p	porous
s	solid cylinder

number of undulations of the wavy wall affect heat transfer characteristics inside the cavity. Misirlioglu et al. [6] studied numerically using the finite element method natural convection inside an inclined wavy cavity filled with a porous medium. Al-Amiri et al. [7] studied numerically mixed convection heat transfer in a lid-driven cavity with sinusoidal heated wavy bottom wall. The vertical walls are adiabatic. They investigated the effect of Richardson number, undulation number and amplitude of the wavy surface on flow structure and heat transfer characteristics. Rostami [8] numerically simulated the unsteady fluid flow and heat transfer behavior in a cavity with vertical wavy walls and horizontal straight walls. Mansour et al. [9] considered numerically the problem of natural convection in wavy porous cavities under the influence of thermal radiation using a thermal non-equilibrium model. Abu-Nada and Chamkha [10] made a computational work of the effects of lid-driven wall on mixed convection flow in a lid-driven cavity with a wavy wall filled with a nanofluid. They found that heat transfer rate increases with the volume fraction of nanoparticles for all values of Richardson numbers and bottom wall geometry ratios. Sheremet and Pop [11] studied the natural convection in a wavy porous cavity filled with a nanofluid and with sinusoidal temperature distributions on both side walls. Recently, Sheremet et al. [12] studied flow and convective heat transfer in a partially heated wavy porous cavity filled with a nanofluid. Cheong et al. [13] considered the internal heat generation effect on natural convection in a wavy porous cavity with sinusoidal heating.

Additionally, due to various engineering applications of the problem of heat transfer and fluid flow around a rotating elements such as chemical mixing devices, rotating-tube heat exchangers, turbo machinery, drilling of oil wells, propulsion and fuel rod in nuclear reactors, etc., this problem has been a subject of interest in various studies for a better understanding of this phenomenon. Studies can be found in the literature related to convection in enclosures with rotating elements especially rotating cylinders. Hayase et al. [14] have investigated the flow and heat transfer between rotating coaxial cylinders with periodically embedded cavities. They showed that the momentum and heat transfer increase by a factor of 1.1 as cavities are embedded in the outer cylinder and by a factor of 1.2 in the case of cavities embedded in the inner cylinder. A numerical study has been carried out by Fu et al. [15] to investigate the natural convection enhancement in a cavity by using a rotating circular cylinder. Kimura et al. [16] analyzed experimentally mixed convection in a rectangular cavity using a rotating plate placed at the center. The effect of rotating solid cylinder on the heat transfer in a square cavity filled with porous medium was firstly considered by Misirlioglu [17]. This study only investigated the effect of rotating solid cylinder on the temperature distribution where it was found that the rotation was more effective in the forced convection regime than in mixed and natural convection regimes. Oztop et al. [18] have performed a numerically mixed convection heat transfer and fluid flow in a lid-driven square enclosure with a circular body. The results of that investigation showed that, the circular body can be a control parameter for heat and fluid flow. Costa and Raimundo [19] have carried out an investigation on the problem of mixed convection heat transfer in a square cavity with a rotating cylinder centered inside it. They analyzed the influence of the cylinder radius, its rotating velocity, its thermal conductivity and its thermal capacity on the mixed convection problem. They have concluded that the rotating cylinder affects the thermal performance of the enclosure and the thermophysical properties of the cylinder are important parameters in controlling heat transfer process in the cavity. Liao and Lin [20] carried out numerical investigation using an immersed-boundary method for natural and mixed convection within a cavity with a heated rotating cylinder. It has been found that the rotation of the cylinder reduced the heat transfer rate. Hussain and Hussein [21] have numerically studied laminar steady mixed convection problem in a 2D square cavity with a conductive rotating circular cylinder enclosed inside it at different vertical locations. The results showed that the location of the rotating cylinder is an important parameter in controlling heat transfer within the enclosure. Recently, Khanafer and Aithal [22] used the commercial software, ADINA to investigate mixed convection heat transfer in a lid-driven cavity with a rotating cylinder. The effects of the dimensionless angular velocity, the