Engineering Science and Technology, an International Journal 19 (2016) 926–945

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

# Analysis of heatlines and entropy generation during double-diffusive MHD natural convection within a tilted sinusoidal corrugated porous enclosure

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ARTICLE INFO

*Article history:*
Received 23 October 2015
Received in revised form
3 December 2015
Accepted 3 December 2015
Available online 27 January 2016

*Keywords:*
MHD
Natural convection
Porous media
Entropy generation
Double diffusive
Corrugated enclosure
Heatline

ABSTRACT

The natural convection and entropy generation during double-diffusive MHD natural convection in a tilted sinusoidal corrugated porous enclosure is investigated numerically in this work by using heatline visualization technique. The top and bottom horizontal walls are assumed as adiabatic and non-diffusive, while the left and right vertical corrugated sidewalls are maintained at a constant hot and cold temperatures and concentrations respectively. The flow in the enclosure is subjected to an inclined magnetic field. The enclosure is filled with an electrically conducting fluid [$Pr = 0.024$] saturated with a porous media. The numerical computations are presented for various values of Rayleigh number (Ra), Hartmann number (Ha), Lewis number (Le), Darcy number (Da), buoyancy ratio (N), magnetic field orientation angle ($\varphi$) and enclosure inclination angle ($\Phi$). In addition, the entropy generation due to fluid friction, thermal gradients, diffusion, and magnetic field beside the total entropy generation are studied and discussed. It is found that the flow circulation decreases strongly when the magnetic field applied horizontally and the enclosure is considered vertical. Heatline visualization concept is successfully applied to the considered problem. The average Nusselt number decreases when the Lewis number increases, while the average Sherwood number increases when the Lewis number increases. Also, both average Nusselt and Sherwood numbers increase when the Darcy number and buoyancy ratio increase. Moreover, the results show that the entropy generations due to magnetic field when the enclosure is subjected to the horizontal magnetic field are higher than the corresponding values when it subjected to the vertical magnetic field.



## 1. Introduction

Natural convection in corrugated or wavy enclosures has an increasing attention in the last ten years. This interest has many reasons. One of them, is due to the many technological application of this geometry like in electronic packages, micro-electronic devices, solar heaters, electric machinery and in geometrical design requirements. The important point one can observe in the open literature is that in spite of the significant practical applications of this geometry, the number of published papers dealing with it is still very limited compared with those discussing classical square, rectangular or inclined walled geometries. This is due to its complex geometry, which makes the construction of the mesh generation and the numerical modeling of it are very difficult to build. Moreover, in corrugated or wavy enclosures, the orientation of their sidewalls is not uniform, but it changes from point to point, which increases also the complexity of the numerical simulation. Furthermore, in wavy enclosures many new important factors that are not encountered in classical geometries must be put in the mathematical model such as wave ratio, inter-wall spacing and amplitude of surface waves. These reasons make the published papers deal with this geometry are very restricted [1–6]. Ali and Husain [7] investigated numerically the natural convection problem in a square enclosure having two vertical sidewalls of vee-corrugated geometry. They concluded that for high Grashof number, the heat transfer rate decreased when the corrugation was decreased. Saha et al. [8] performed a numerical analysis using finite element method on steady-state natural convection in a vee-corrugated square enclosure with discrete heating from below. The length of the heat source was 20% of the total length of the bottom wall. The non-heated parts of the bottom wall and entire upper wall were considered adiabatic. The Grashof number based on the enclosure height varied from $10^3$ to $10^6$, corrugated frequency varied from 0.5 to 2 and Prandtl number was taken as 0.71. The results showed that the average Nusselt number was maximum for low

*Abbreviation:* MHD, magneto-hydrodynamics.

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.12.001
2215-0986/

corrugation frequency but a reverse trend was found for high corrugation frequency. Hasan et al. [9] numerically investigated the natural convection of air in a two-dimensional laminar steady-state incompressible fluid flow in a modified square enclosure with a sinusoidal corrugated top surface for different inclination angles. A constant flux heat source was flush mounted on the top sinusoidal wall, modeling a wavy tin shaded room exposed to sunlight. The results were obtained for Rayleigh number (Ra) ranging from $10^3$ to $10^6$. The results showed that the convective phenomena were greatly influenced by the variation of inclination angles. Saha et al. [10] carried out a numerical simulation to study the effects of discrete isoflux heat source size and angle of inclination on natural convection inside a sinusoidal corrugated inclined enclosure. They concluded that for various heat source sizes, when the angle of inclination was increased, the overall Nusselt number was increased also. Hussain et al. [11] studied numerically the steady natural convection phenomenon in a square inclined enclosure with vertical vee-corrugated sidewalls and horizontal top and bottom surfaces. A discrete heat flux strip of 24% of the total length was flush-mounted on the bottom wall, while the other non-heated parts of the bottom wall and the top wall were considered adiabatic. The two vee-corrugated sidewalls were maintained at constant cold temperature. They concluded that the natural convection phenomenon was greatly affected by increasing the enclosure inclination angle. Bakier [12] studied numerically, by using the finite difference scheme, the free convection in partially C-shape open ended enclosure filled with water-based nanofluid. They concluded that the nanofluid increased both the rate of the heat and mass transfer in the enclosure. Also, he concluded that stream function was decreased by increasing the aspect ratio. Mliki et al. [13] used the Lattice Boltzmann method to simulate numerically the free convection in an L-shaped enclosure filled with copper–water nanofluid. They concluded that heat transfer was increased when the aspect ratio was low.

The natural convection in wavy enclosures filled with electrically conducting fluid subjected to a magnetic field or a fluid saturated with a porous media has a wide range of industrial applications such as sewage purification in sand beds, water storage in heavy porous rocks and nuclear fusion. Examples of recent studies considering the natural convection in wavy enclosures or surfaces subject to a magnetic field or filled with a porous media are reviewed in the following sections. Kumar [14] studied numerically the free convection induced by a vertical wavy surface with heat flux in an enclosure filled with porous medium. He concluded that the surface temperature was very sensitive to drifts in undulations and amplitude of the wavy surface. Misirlioglu et al. [15] numerically investigated the steady-state free convection inside a cavity made of two horizontal adiabatic straight walls and two isothermal vertical bent-wavy walls and filled with a fluid-saturated porous medium. The wavy walls were assumed to follow a profile of cosine curve. Flow and heat transfer characteristics (isothermal, streamlines and local and average Nusselt numbers) were investigated for some values of Rayleigh number, cavity aspect ratio and surface waviness parameter. Misirlioglu et al. [16] performed a numerical investigation by using the finite element method of free convection inside a cavity made of two horizontal adiabatic straight walls and two isothermal vertical wavy walls filled with a heat-generating porous medium. Simulations were carried out for a range of wave ratio [$\lambda$ = 0 to 0.6], aspect ratio [A = 1 to 5] and Rayleigh number [Ra = 10 to 1000]. Results were presented in the form of streamlines, isotherms and local and average Nusselt numbers. Khanafer et al. [17] carried out a numerical investigation to analyze natural convection inside a cavity with a sinusoidal vertical wavy wall and filled with a porous medium. The vertical walls were isothermal while the top and bottom horizontal straight walls were kept adiabatic. The implications of Rayleigh number, number of wavy surface undulation and amplitude of the wavy surface on the flow structure and heat transfer characteristics were investigated in detail while the Prandtl number was considered equal to unity. Mushatet [18] numerically studied the natural convection in an inclined wavy porous cavity. The two wavy walls were differentially heated, while the upper and lower walls were insulated. The problem was simulated for different values of Rayleigh number [$50 \le Ra \le 500$] and angle of inclination [$0° \le \alpha \le 90°$]. He concluded that the angle of inclination, number of undulation, the amplitude and Rayleigh number had a significant effect on the flow and thermal field. Also, it was found that the heat transfer rate was increased as angle of inclination increased. Mansour et al. [19] studied numerically by using thermal non-equilibrium model the steady natural convection inside wavy enclosures with the effect of thermal radiation. The inter-phase heat transfer coefficient effect, thermal radiation effect, the modified conductivity ratio effect and the Rayleigh number effect were investigated and discussed. They concluded that the average Nusselt number decreased by increasing the modified conductivity ratio. Whereas, increasing the radiation parameter led to the increase in the average Nusselt numbers for fluid and solid phases. Saha [20] studied numerically the magnetohydrodynamic natural convection in a sinusoidal corrugated air-filled enclosure with discrete isoflux heating from below. The results explained that streamlines and isotherms were affected significantly for high Grashof number and zero Hartmann number. Hussain et al. [21] analyzed numerically the effects of the longitudinal magnetic field and the heat source size on natural convection in a tilted sinusoidal corrugated enclosure for different values of enclosure inclination angles. A constant heat flux source was discretely embedded at the central part of the bottom wall, whereas the remaining parts of the bottom wall and the upper wall were assumed adiabatic. The two vertical sinusoidal corrugated walls were maintained at a constant low temperature. An empirical correlation was developed by using Nusselt number versus Hartmann number, Rayleigh number and enclosure inclination angle. They concluded that the increase in the Hartmann number and the ratio of heating element to enclosure width decreased the Nusselt number. Moreover, double-diffusive natural convection in corrugated or wavy enclosures or surfaces has an important applications in various engineering fields such as food industries, solidification in material processing, chemical engineering, cement manufacturing and oil tanks. In this type of heat transfer process, the natural convection is generated due to both temperature and concentration effects. Rathish Kumar and Krishna Murthy [22] analyzed the combined heat and mass transfer process by natural convection from a corrugated vertical surface immersed in a non-Darcy porous medium. Krishna Murthy et al. [23] investigated numerically the double diffusive free convection due to corrugated vertical surface immersed in a fluid saturated semi-infinite porous medium under Darcian assumptions. The effect of various parameters such as wave amplitude (a), Lewis number (Le), buoyancy ratio (B), and Soret ($S_r$) and Dufour ($D_f$) numbers were analyzed through local and average Nusselt number, and local and average Sherwood number plots. Rahman et al. [24] performed a numerical study of double-diffusive buoyancy induced flow in a triangular cavity with corrugated bottom wall. The results were presented for various wave lengths ($0.1 \le \lambda \le 1.0$), Rayleigh number ($10^3 \le Ra \le 10^5$) and Prandtl number ($0.071 \le Pr \le 7$). It was found that wave length played a dominant role on flow strength for any Rayleigh numbers. Nikbakhti and Khodakhah [25] made a numerical investigation by using the finite difference method about the double diffusive natural convection in a cavity partially heated and cooled from sidewalls. They found that in the aiding flow, the average Nusselt number was increased with increasing the buoyancy ratio. From the other side, the heat transfer process is considered as an irreversible process, so it already generates entropy. Therefore, to get an optimum heat transfer process it is very recommended to reduce the entropy generation. However, the entropy generation due to natural convection in a corrugated or wavy enclosure has