Energy 64 (2014) 69–94

Contents lists available at ScienceDirect

Energy

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

Bejan's heatlines and numerical visualization of convective heat flow in differentially heated enclosures with concave/convex side walls

Pratibha Biswal, Tanmay Basak*

Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 4 January 2013
Received in revised form
7 October 2013
Accepted 11 October 2013
Available online 5 December 2013

Keywords:
Natural convection
Curved enclosures
Streamlines
Heatlines
Nusselt number
Thermal management

ABSTRACT

Numerical simulation for natural convection flow in fluid filled enclosures with curved side walls is carried out for various fluids with several Prandtl numbers ($Pr = 0.015$, 0.7 and 1000) in the range of Rayleigh numbers ($Ra = 10^3$–10^6) for various cases based on convexity/concavity of the curved side walls using the Galerkin finite element method. Results show that patterns of streamlines and heatlines are largely influenced by wall curvature in concave cases. At low *Ra*, the enclosure with highest wall concavity offers largest heat transfer rate. On the other hand, at high *Ra*, heatline cells are segregated and thus heat transfer rate was observed to be least for highest concavity case. In convex cases, no significant variations in heat and flow distributions are observed with increase in convexity of side walls. At high *Ra* and *Pr*, heat transfer rate is observed to be enhanced greatly with increase in wall convexity. Results indicate that enhanced thermal mixing is observed in convex cases compared to concave cases. Comparative study of average Nusselt number of a standard square enclosure with concave and convex cases is also carried out. In conduction dominant regime (low *Ra*), concave cases exhibit higher heat transfer rates compared to square enclosure. At high *Ra*, low *Pr*, concave cases with $P_1P_1' = 0.4$ is advantageous based on flow separation and enhanced local heat transfer rates.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Natural convection is the mode of heat transfer where buoyancy forces govern the fluid motion. Study of natural convection in confined cavities as well as in open channels has received significant attention due to versatile natural, industrial and engineering applications, especially those associated with conservation of energy. Some of the important industrial and engineering applications of natural convection are cooling of electronic devices [1], thermal storage tanks [2], nuclear reactors [3], proper ventilation and thermal comfort in buildings [4,5], efficient design of buildings [6], analyzing thermal storage characteristics of aluminum [7], drying of fruit and vegetables using solar dryer [8], enhanced gas recovery [9] etc. Also, knowledge of natural convection plays a significant role in the design strategy of solar energy collectors which involves efficient collection, storage and distribution of solar energy [10]. A good amount of research has been carried out to understand the role of natural convection in solar energy field [11–14]. In above mentioned applications, natural convection plays a vital role in conservation of energy through efficient heat transfer process. In order to analyze heat efficiency in a system, it is required to assess the amount of heat transfer. Thus, study of natural convection in enclosure with various geometric configuration, especially enclosure with curved walls may be relevant in many heat transfer applications. In energy point of view, it is important to show the direction and intensity of energy flow during natural convection in an enclosure. Knowledge of direction and intensity of energy flow during natural convection in complicated cavities as considered in current work may be used in design of various thermal equipments with better thermal performance.

Investigations of natural convection in a confined cavity in presence of various boundary conditions with different parameters have been carried out by researchers for various energy related applications [15,16]. Several studies on buoyancy driven flow within triangular enclosures have been carried out by researchers for proper design and ventilation in rooms [17–19]. Natural convection in air filled 2D tilted square cavities and parallelogrammic cavities for various geometrical and thermal configurations was investigated by Bairi [20,21]. All above mentioned works have been carried out to understand natural convective heat flow within regular and irregular enclosures with flat wall. In contrast, there are limited number of studies with curved walled enclosures because of complexity of flow inside the enclosure due to complicated geometry. Wall curvature of the curved wall is considered to be one of

* Corresponding author. Tel.: +91 44 2257 4173; fax: +91 44 2257 0509.
E-mail address: tanmay@iitm.ac.in (T. Basak).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.10.032

the important parameters for assessment of heat flow, fluid flow and thermal characteristics of the fluid within the enclosure.

Natural convection heat transfer within enclosures with curved or wavy surfaces is very often used in microelectronic industries [22], solar energy systems [23], solidification process [24] etc. Cooling process of water in a circular enclosure subjected to non-uniform boundary conditions is studied by Alawadhi [25]. Further, Alawadhi [26] also investigated solidification process of water inside an elliptical enclosure with various aspect ratios and inclination angles. Gao et al. [27] conducted a numerical study on natural convection inside channel between the flat-plate cover and the sine-wave absorber in a cross-corrugated solar air heater.

Investigations on natural convection as mentioned above, have been analyzed based on conventional streamline and isotherm concepts which are not adequate to understand direction and intensity of convective heat transfer. Current work is devoted to analyze the distribution of heat flow associated with natural convection within an enclosure with curved side walls using heatline method. Heatlines concept was first introduced by Kimura and Bejan [28]. Mathematically, magnitudes of heatlines are represented by heatfunctions which are further related to the Nusselt number. A unified approach for streamline, heatline and massline methods to visualize two dimensional transport phenomena is implemented by Costa [29]. An extensive review on Bejan's heatlines and masslines for convection heat transfer and mass transfer visualization, respectively was also presented by Costa [30]. Further, Dalal and Das [31] studied heatline method for the visualization of natural convective heat flow in a complicated cavity.

Several enclosures with various geometrical orientations subjected to different boundary conditions have been considered for heatline based heat flow visualization of natural convection. Kaluri and Basak [32] analyzed Bejan's heatlines and thermal mixing during natural convection in a square enclosure with distributed heat sources. In addition, earlier numerical investigations on heat flow visualization during natural convection within the square enclosure [33], tilted square enclosure [34,35], triangular enclosure [36], rhombic enclosure [37] and trapezoidal enclosure [38] with various uniform and non-uniform heating of the wall are found in the literature. In all the above mentioned works, the Galerkin finite element method is employed to solve the governing equations for various boundary conditions. Earlier works were carried out with the heatline analysis of natural convection in enclosures involving regular geometries with straight walls. The finite element method has also an advantage to study natural convection problems within complicated domains with curved walls involving heatfunction evaluation via automatically built-in complex boundary conditions via Galerkin weighted residual. The complete understanding on heat flow visualization with thermal management via heatline method in various cavities with convex or concave side walls has industrial relevance and these analyses are reported for first time in this paper.

The aim of the present paper is to provide a complete understanding about the fluid flow, heat flow and thermal characteristics within cavities with curved side walls. The concave and convex side walls are chosen to investigate efficient thermal management via heatline approach and the major objective of this work is to study the distribution of heat and fluid flow within the cavity. Current physical configurations with various curved side walls can be used in design of various heat transfer devices such as solar collectors, heat exchangers, storage and cooling devices. The cavity is subjected to various boundary conditions such as isothermally hot left wall, isothermally cold right wall and adiabatic horizontal walls. The Galerkin finite element method with penalty parameter [39] is used to solve the nonlinear coupled partial differential equations governing the flow and thermal fields and the finite element method is further used to solve the Poisson equation for streamfunction and heatfunction. Numerical results are obtained to display the streamlines, heatlines and isotherms for various Rayleigh numbers ($10^3 \le Ra \le 10^6$), Prandtl numbers ($Pr = 0.015$, 0.7 and 1000) and wall curvatures. The heat transfer rates along the curved side walls are presented in terms of local and average Nusselt numbers.

2. Mathematical modeling and simulations

The physical domain in three dimensional form is shown in Fig. 1(a–b). The computational domain is shown in Fig. 1(c) based on semi-infinite approximation along Z direction. Thermo-physical properties of the fluid in the flow field are assumed to be constant except density. The variation of density with temperature can be calculated using Boussinesq approximation. In this way, the temperature field and flow fields are coupled. Under these assumptions, governing equations for steady two-dimensional natural convection flow in the enclosure with curved side walls using conservation of mass, momentum and energy can be written with following dimensionless variables or numbers:

$$X = \frac{x}{L}, \quad Y = \frac{y}{L}, \quad U = \frac{uL}{\alpha}, \quad V = \frac{vL}{\alpha}, \quad \theta = \frac{T - T_c}{T_h - T_c}$$

$$P = \frac{pL^2}{\rho\alpha^2}, \quad Pr = \frac{\nu}{\alpha}, \quad Ra = \frac{g\beta(T_h - T_c)L^3 Pr}{\nu^2}.$$

Here x and y are the distances measured along the horizontal and vertical directions, respectively; u and v are the velocity components in the x and y directions, respectively; T denotes the temperature; ν and α are kinematic viscosity and thermal diffusivity, respectively; β denotes the volume expansion coefficient; p is the pressure and ρ is the density; T_h and T_c are the temperatures at hot left wall and cold right wall, respectively and L is the height or length of the base of the cavity. Note that, X and Y are dimensionless coordinates varying along horizontal and vertical directions, respectively; U and V are dimensionless velocity components in the X and Y directions, respectively; θ is the dimensionless temperature; P is the dimensionless pressure and Ra and Pr are Rayleigh and Prandtl number, respectively. The governing equations in dimensionless forms for continuity [Eq. (1)], momentum balance [Eqs. (2) and (3)] and energy balance [Eq. (4)] are as follows:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0, \tag{1}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right), \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + RaPr\theta, \tag{3}$$

and

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \tag{4}$$

and the governing equations [Eqs. (2)–(4)] are subjected to the following boundary conditions;

Download English Version:

https://daneshyari.com/en/article/8078635

Download Persian Version:

https://daneshyari.com/article/8078635

Daneshyari.com