International Journal of Heat and Mass Transfer 112 (2017) 489–508

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Role of discrete heating on the efficient thermal management within porous square and triangular enclosures via heatline approach

Debayan Das, Tanmay Basak *

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

A R T I C L E I N F O

Article history:
Received 28 November 2016
Received in revised form 14 April 2017
Accepted 18 April 2017

Keywords:
Natural convection
Porous media
Discrete heating
Triangular enclosure
Heatline
Thermal management

A B S T R A C T

The conventional method of differential heating within an enclosure may result in the inadequate thermal mixing and that may further lead to the poor thermal management. In order to enhance the overall thermal mixing, the discrete heating strategy may be considered as an effective alternative. In the current work, natural convection studies have been carried out within discretely heated porous square and triangular (type 1 and type 2) enclosures during natural convection. Overall, five different discrete heating strategies (cases 1–4: symmetric heating, case 5: asymmetric heating) have been considered for the present work. The heatline method has been implemented to visualize the heat flow pattern within the cavities for a wide range of parameters ($Pr_m = 0.015—7.2$, $Da_m = 10^{-5}—10^{-2}$, $Ra_m = 10^6$). In order to solve the governing equations and Poisson equations for streamfunction and heatfunction, the Galerkin finite element method has been used. At $Da_m = 10^{-4}$, computational results clearly indicate the onset of convection whereas enhanced convection is found to occur at $Da_m = 10^{-2}$ based on the presence of intense fluid and heatline cells. The intensity of heat flow is observed to be higher for the asymmetric distributed heating strategy compared to the symmetric distributed heating configurations. Heatlines depict the role of hot regime along the side walls and they are also useful in explaining the variations of the local and average Nusselt numbers for the various cases. Common to all the cases, the average heat transfer rate within the triangular- type 1 enclosure is higher compared to the square and triangular-type 2 enclosures irrespective of Da_m and Pr_m. The extent of the thermal mixing in each case has been quantified using the cup-mixing temperature which has been evaluated at higher and lower Da_m in order to establish the effect of porosity. It is concluded that the thermal mixing is more effective within the square and triangular-type 2 enclosures at both $Da_m = 10^{-4}$ and 10^{-2}. The cases 2 and 5 were inferred to be the optimal discrete heating strategies.

1. Introduction

Natural convection phenomenon plays a significant role in various industrial and thermal processes such as cooling of electronic components [1], chemical and material processing [2–6] packed bed reactors [7], food processing [8], polymer processing [9], casting of manufacturing processes [10–12] and alloy casting [13,14]. Natural convection within the different enclosures filled with fluid saturated porous media have received considerable attention in the recent past. Many of the recent books [15–17] have consolidated various applications of porous enclosures.

In the recent past, considerable number of studies have been carried out based on natural convection in porous media [18–26]. Researchers have implemented various heating strategies within the porous enclosures. One such heating strategy is the differential heating which involves the isothermal heating of one of the vertical walls while the isothermal cooling is employed at other vertical walls in the presence of insulated horizontal walls [27–33]. In a differentially heating system, heat from the hot wall diffuses faster to the core but takes higher time to penetrate to the opposite cold wall. Thus, the overall thermal mixing within the enclosure tends to be poor and also a large non-uniformity in temperature prevails throughout the enclosure. This may finally lead to the poor thermal management within enclosures. Thus, in the present study, it is proposed to divide and distribute the heaters along both the vertical walls while implementing the identical heat input of the differential heating. It may be noted that the buoyancy flow is induced locally within the enclosures due to the distributed heat sources and that finally results in the enhancement of the thermal mixing throughout the enclosure. Hence, the thermal mixing in the dis-

---

* Corresponding author.

E-mail addresses: debayan8221@gmail.com (D. Das), tanmay@iitm.ac.in (T. Basak).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.083
0017-9310/

Nomenclature

C_{p_f}	specific heat capacity of the fluid, J kg K^{-1}
Da_m	modified Darcy number
g	acceleration due to gravity, m s^{-2}
k_{eff}	effective thermal conductivity, W m^{-1} K^{-1}
K	permeability, m^2
K_m	modified permeability, m^2
L	height of the triangular enclosure, m
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr_m	modified Prandtl number
Ra_m	modified Rayleigh number
T	temperature of the fluid, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
u	x component of velocity, m s^{-1}
U	x component of dimensionless velocity
v	y component of velocity, m s^{-1}
V	y component of dimensionless velocity
x	distance along x coordinate, m
X	dimensionless distance along x coordinate
y	distance along y coordinate, m
Y	dimensionless distance along y coordinate

Greek symbols

α_{eff}	effective thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
γ	penalty parameter
ν	kinematic viscosity, m^2 s^{-1}
ν_f	kinematic viscosity of the fluid, m^2 s^{-1}
ρ	density, kg m^{-3}
ρ_f	density of the fluid, kg m^{-3}
φ	angle with positive X-axis
ψ	dimensionless streamfunction
Π	dimensionless heatfunction
ϵ	porosity of the medium

Subscripts

ll	length of the left wall
rl	length of the right wall

cretely heated cavities is anticipated to be significantly higher compared to the differential heating technique. Note that, only few studies can be found in literature involving natural convection in porous enclosures subjected to discrete heating from the side walls [34–39]. However, existing works do not highlight the extent of thermal mixing or the overall thermal management involving various locations of multiple discrete heaters at the side walls.

In most of the earlier works, streamlines and isotherms have been used to analyze the numerical results of convective heat transfer. It is found that fluid flow in a system can be adequately visualized using streamlines. However, the energy or heat distribution in a system cannot be rightly predicted by isotherms especially in the convection dominant regime. Heatlines have emerged as one of the important mathematical tools for the visualization of the energy paths or heat flows within the cavities [40]. A complete review of earlier works on heatline analysis is found elsewhere [41]. It may be noted that heatlines along with isotherms and streamlines are effective in estimating the thermal management within various cavities. The heat flow visualization plays an important role in order to predict the effect of the heaters on the energy flow inside the cavities. In a recent article, Bejan [42] compared "heatlines" and "synergy" concepts. It was reported that synergy is merely a replication of heatlines and synergy is not related to the heat transfer enhancement technique unless there is a change in geometrical configurations or special inserts to accelerate the flow [42]. Various researchers have implemented the concept of heatlines for the effective visualization of the energy flow in the porous cavities [43–50]. However, only few works based on heatline studies within the discretely heated porous enclosures are available in literature [51]. Kaluri and Basak [51] carried out heatline analysis in porous square cavities subjected to the discrete heating from the bottom and side walls. It was concluded that, the method of 'heatline' is an essential mathematical tool in order to establish suitable heating strategies.

It is worthwhile to mention that the thermal mixing studies in the porous triangular cavities is yet to be carried out and the present work will be an important addition to the existing literature. Also, the thermal mixing studies in the porous triangular cavities have been compared with a porous square cavity of identical area. The present work involves five different cases based on various symmetric/asymmetric locations of discrete heaters at the vertical wall for (i) square (ii) triangular-type 1 and (iii) triangular-type 2 cavities. Darcy-Brinkman-Forchheimer formulation has been used to predict the flow in the porous medium. Galerkin finite element method is used to solve the governing equations of flow and temperature fields. The fluid and heat flow visualization along with the temperature distribution for various Da_m ($Da_m = 10^{-5} - 10^{-2}$) and Pr_m ($Pr_m = 0.015$ and 7.2) at the high Ra_m ($Ra_m = 10^6$) are illustrated with streamlines, heatlines and isotherms. The heat transfer rate in the square and triangular cavities is evaluated in terms of the local and average Nusselt number. Further, in order to estimate the extent of the thermal mixing, Θ_{cup} is evaluated for all the cases. In addition, $RMSD_{\Theta_{cup}}$ is also assessed in order to elucidate the degree of temperature uniformity within the cavities.

2. Mathematical formulation and simulation

The physical and computational domains of the square and triangular (type 1 and type 2) enclosures along with the discrete heaters are shown in Figs. 1a(i-iii) (physical domain) and 1b(i-iii) (computational domain). Table 1 refers to the dimensionless lengths of the different isothermal cold and hot zones situated on the side walls of the cavities. The thick solid lines along the side walls denote the discrete heaters (isothermal heat source, Figs. 1b (i-iii)). The horizontal walls of the square and triangular (type 1 and type 2) enclosures are maintained adiabatic (Fig. 1b(i-iii)). Isothermally cold condition is maintained along the rest of the portions of the side walls are maintained. The total dimensionless length of the heaters within the cavities is 1 whereas, the dimensionless length of the total adiabatic wall(s) of the cavities corresponds to 2. The overall area of the square and triangular (type 1 and type 2) cavities is 1 square unit and they possess the identical amount of fluids. The first four cases (cases 1–4) involve the symmetric locations of heaters along the side walls within the square and triangular (type 1 and type 2) enclosures. On the other hand,