International Journal of Heat and Mass Transfer 114 (2017) 430–452

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Enhanced convective heat transfer in lid-driven porous cavity with aspiration

Nirmalendu Biswas, Nirmal K. Manna *

*Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India*

ARTICLE INFO

*Article history:*
Received 29 January 2017
Received in revised form 9 May 2017
Accepted 16 June 2017

*Keywords:*
Lid-driven cavity
Porous medium
Aspirated cavity
Thermal convection
Heat transfer enhancement

ABSTRACT

A scope of enhancing heat transfer during thermal convection in enclosure is explored in this work considering the free aspiration of surrounding fluid. The illustration is made using a two-sided lid-driven porous cavity under differential heating, which is expanded into possible four (assisting, opposing, upward and downward) flow-configurations. The aspiration ports are provided diagonally opposite corners for partial inflow of cold surrounding fluid and partial venting of hot cavity fluid. It leads to primary (or bottom) aspiration and depending upon the direction of sidewall motion, secondary (or top) aspiration. The resulting complex mixed-flow (shear flow, buoyant flow and aspirated flow) through porous medium is modeled by applying Brinkman-Forchheimer-Darcy model (BFDM) and Boussinesq approximation. The evolved nonlinear-coupled equations are solved by an in-house code for the wide ranges of parameters (Reynolds number $Re = 10–500$, Richardson number $Ri = 0.1–100$), Darcy number $Da = 10^{-3}–10^{-7}$ and porosity $\varepsilon = 0.1–1$) rigorously. The results reveal heightened heat transfer from the aspirated cavity compared to the identical non-aspirated cavity. Depending upon the combination of the parameters, the enhancement could be as high as ~180%. The upward-flow configuration yields the maximum heat transfer when no external baffle is used for flow partitioning during the case of top aspiration. With the baffle, the opposing flow shows the maximum heat transfer of ~339%. The study reveals that the aspiration can magnificently enhance heat transfer without any additional expenses for pumping power of it.

## 1. Introduction

Due to the multitudinous nature of thermal convective flow in channels/cavities and its existence in many fields of engineering and technology, the serious research on thermal convection still on present date is relevance and essential. The thermal convective flow may also involve with multi-physical conditions (such as the presence of porous-medium, double diffusion, Marangoni convection, nanofluids, magneto-hydrodynamics, etc.). To explore the new ideas or to fulfill the ever-increasing demand on enhanced performance, energy efficiency and size reduction/miniaturization of the systems and devices involving with thermal convection, drives the current research in this area. Literature review shows a considerable volume of researches continuing in every year on the thermal convection. For examples, only on the porous square cavity, a number of studies are conducted recently considering nanofluids [1–4], double-diffusion [5,6], magnetic field [1,7–9], lattice Boltzmann model [5,10], moving walls and heatlines [11], sinusoidal heating [12], coupling with thermal radiation [13], double lid-driven sinusoidally-heated cavity [14] and others. The thermal convective mode of heat transfer is utilized in many areas such as cooling of electronic and electrical equipments, geothermal energy systems, solar heating, storage of nuclear waste, oil and gas production, separation process in chemical industries, grains and food processing, storage of granular materials, biological systems and others. Its applications in different fields as is governed by various combinations of thermal as well as velocity conditions of boundary walls along with the kind of working substances, the study on different (or similar) problem geometries under different imposed boundary conditions [15–25] is essential to unearth the fundamental aspects of involved flow physics.

The importance of lid-driven porous cavities and their applications in many fields are established in a large numbers of earlier works [9,11,14,21,25–37]. The fluid flow and heat transfer in the lid-driven channel/cavity is governed by wall motion and natural convection. The wall motion induces shear flow of fluid adjacent to the moving sidewalls of the cavity, whereas natural convection evolves from thermal gradient. In the presence of both shear flow

---

* Corresponding author.

*E-mail addresses:* nirmalendubiswas@yahoo.co.in (N. Biswas), nirmalkmannaju@gmail.com (N.K. Manna).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.078

**Nomenclature**

| | |
|---|---|
| $Da$ | Darcy number |
| $F_C$ | Forchheimer coefficient, $m^{-1}$ |
| $g$ | acceleration due to gravity, $m/s^2$ |
| $Gr$ | Grashof number |
| $H$ | height of the cavity/length scale, m |
| $K$ | permeability of porous medium, $m^2$ |
| $L$ | length of the cavity, m |
| $\dot{m}$ | dimensionless mass flow rate |
| $Nu$ | average Nusselt number |
| $p$ | pressure, Pa |
| $P$ | dimensionless pressure |
| $Pr$ | Prandtl number |
| $\dot{q}$ | dimensionless heat flow rate |
| $Re$ | Reynolds number |
| $Ri$ | Richardson number, $Gr/Re^2$ |
| $T$ | temperature, K |
| $u, v$ | velocity components, m/s |
| $U, V$ | dimensionless velocity components |
| $w$ | opening width for aspirated port, m |
| $x, y$ | Cartesian coordinates, m |
| $X, Y$ | dimensionless coordinates |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, $m^2/s$ |
| $\beta$ | volumetric thermal expansion coefficient of fluid, $K^{-1}$ |
| $\psi$ | dimensionless stream function |
| $\theta$ | dimensionless temperature |
| $\eta$ | heat transfer parameter |
| $\varepsilon$ | porosity |
| $\nu$ | kinematic viscosity, $m^2/s$ |
| $\rho$ | density, $kg/m^3$ |

*Superscripts*

| | |
|---|---|
| +, – | up, down direction of wall motion |

*Subscripts*

| | |
|---|---|
| $a$ | ambient, cold wall/fluid, aspiration |
| $h$ | hot wall |
| $i$ | inflow |
| $o$ | outflow |

and thermal convection, the dynamics of fluid flow and heat transfer becomes complex as they are intrinsically coupled to each other. The complexity further arises with the simultaneous motion of two or more walls those can translate in same or different directions. Different thermal conditions of the walls complicate the heat transfer process more in presence of porous medium as found in [25,28–30] where it is reported that the variation of average Nusselt number is non-linear for the increasing values of the Darcy number. The complexity in heat and fluid flow characteristics is found to increase depending upon the direction and number of moving wall when the cavity is driven by from one lid [30,31] to two [29,32–34] or more. The lid-driven square and rectangular cavities filled with porous medium were investigated by Yang et al. [35] using Brinkman–Forchheimer model. They reported considerable effect of porous media on the flow field. Lid-driven flow in a non-Darcy porous cavity was investigated by Aly and Asai [36] and they found to increase flow velocity and average Nusselt number as porosity increases. Kandaswamy et al. [37] numerically investigated mixed convection in a lid-driven square cavity filled with a fluid-saturated porous medium. They found that the conduction dominates at low Prandtl number while with the increasing Prandtl number, mixed convection and forced convection dominate the temperature field. Other class of works on mixed convection involving flow over vertical surface embedded in porous medium was also conducted [38,39]. All these studies highlight the heat and fluid flow characteristics of porous system under the influence of different parameters.

Mixed convection under completely filled [40,41] or partially filled [42–44] porous medium in a vented cavity has been analyzed. Mahmud and Pop [41] have numerically studied steady mixed convection in a vented porous enclosure with an isothermal vertical wall. The impact of outlet port positions of a vented porous square cavity undergoing laminar mixed convection has been investigated by Ghazanfarian and Abbassi [42]. Unsteady mixed convection in a ventilated rectangular cavity is studied by Moraga et al. [43] considering two horizontal layers of porous media of different permeabilities and their results highlight the effects of different parameters on flow and heat transfer rate. Al-Amiri and Khanafer [44] have numerically investigated heat transfer in a ventilated porous cavity considering thermal conductivity of porous medium. Numerical simulation of mixed convection heat transfer of an incompressible fluid-filled horizontal channel has been analyzed by Jaballah et al. [45] in the presence of some porous blocks. Using porous cavity inside a horizontal channel, the cooling a heated surface by jet impingement and under opposing mixed convection flow has been numerically analyzed by Wong and Saeid [46]. A detailed account of review on thermal convection and the classical treatment on the transport phenomena in porous media, have already been reported by Vafai and Tien [47], Bejan et al. [48], Ingham and Pop [49], Vafai [50], Nield and Bejan [51] and Bejan [52]. Studies on mixed convection in the presence of porous medium have also been extended in different directions like magneto-hydrodynamic (MHD) flow [53,54] and nanofluids [55].

For energy efficiency improvement and compactness or miniaturization of different devices along with the higher performance outcome, heat transfer enhancement becomes utmost important. In this direction, some efforts for improving heat transfer are already demonstrated in our recent works [56–63] using simple means [56–59] or methods [60–63] like the insertion of baffle [56] or block [57–59] in the flow domain. In Datta et al. [59] using an adiabatic block, heat transfer enhancement is illustrated for a differentially heated porous cavity. Heat transfer during natural convection can also be enhanced with the increase of the pulsating frequency of alternately active bi-heater system [60] and through sinusoidal heating (in place of uniform heating) [61]. Under mixed convection flow, an efficient method of managing thermal load along the boundary walls is addressed through a segmental heating approach [62] and an injection tapped from the main flow [63]. In the present work, another striking impact of free aspiration on the enhancement of heat transfer is addressed.

The study of free aspiration in lid-driven cavity with porous medium is chosen from many vital reasons as follows. The above-mentioned literature survey indicates that mixed convection in cavities filled with porous medium have been studied considering wall motion or external flow. The use and importance of lid-driven porous cavities in many fields are mentioned in many works [9,11,14,21,25–37]. However, to maintain lid motion, some work energy is needed. In order to reduce this work input or to