International Journal of Academic Research
ISSN: 2348-7666; Vol.5, Issue-10, October, 2018
Impact Factor: 6.023; Email: drtvramana@yahoo.co.in

Heat transfer in porous media of trapezoidal section

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Abstract: The study of natural convection in porous media has wide applicability in various natural and industrial processes e.g. fluid flow in geothermal reservoirs, dispersion of chemical contaminants through water saturated soil, petroleum extraction, migration of moisture in grain storage systems, building thermal insulations and catalytic reactions. The main attribute for choosing the trapezoidal shape cavity is to enhance the heat transfer rate due to its extended hot bottom surface. These types of cavities are used to store heat using porous material underground and for heat transfer in a solar trapezoidal cavity absorber for solar collectors. The flow inside these cavities is much more complicated to investigate, as the boundary zone and the middle core zone do not have the same effect for a certain considered boundary condition. Heat line visualization technique is a useful method that gives information on heat transport from the hot to cold region inside the porous trapezoidal enclosure with varying temperature boundary conditions. Nusselt numbers are computed for Darcy- modified Rayleigh numbers or Rayleigh number (Ra) ranging from 100 to 2000 for an aspect ratio (H/L) of 0.5 for the cavity. The power law correlations between average Nusselt number and Rayleigh numbers are presented for convection dominated regions. The average Nusselt number increases monotonically with increase of Ra for both top and bottom walls. It has been observed that the average Nusselt number for the case of uniform bottom wall is more than that of linearly and sinusoidally varying temperature cases at the hot and cold walls.

Key words: Heat Transfer, Nusselt number, Radiation

Introduction

Typically by a porous medium we mean a material consisting of a solid matrix with an interconnected void. The solid matrix is either rigid or undergoes small deformation. The interconnection of the void (the pores) allows the flow of one or more fluids through the material. In the simplest situation ("single phase flow") the void is saturated by a single fluid, while in two phase flow gas and liquid share the same void space. The porosity φ of a porous medium is defined as the fraction of the total volume of the medium that is occupied by void space.

Natural convection in porous media has wide applicability in various natural and industrial processes e.g. fluid flow in geothermal reservoirs, dispersion of chemical contaminants through water saturated soil, petroleum extraction, migration of moisture in grain storage systems, building thermal insulations, catalytic reactions For this reason, this mode of heat transfer has been extensively studied experimentally as well as analytically and numerically for different flow aspects. Porous media is used because of following features.

Its dissipation area is greater than the conventional fins thereby enhancing heat convection.

The irregular motion of the fluid flow around the individual pores mixes the fluid more effectively.

In a natural porous medium the distribution of pores with respect to shape and size is irregular. On the pore scale (microscopic scale) the flow quantities (velocity, pressure etc.) will be clearly irregular. But in typical experiments the quantities of interest are measured over areas that cross many pores, and such space-averaged (macroscopic) quantities change in a regular manner with respect to space and time, and hence are amenable to theoretical treatment. How we treat a flow through a porous structure is largely a question of distance, which is the distance between the problem on hand and the actual flow structure.

When the distance is short, the observer sees only one or two channels, or one or two open or closed cavities. In this case it is possible to use the conventional fluid mechanics and convective heat transfer to describe what happens at every point of fluid and solid-filled spaces. When the distance is large so that there are many channels and cavities in the problem solver's field of vision, the complications of the flow paths rule out the conventional approach. In this limit, volume-averaging and global-measurements (ex: permeability, conductivity) are useful in describing the flow in simplifying the description. As engineers focus more and more on designing porous media at decreasing pore scales, the problems tend to fall between the extremes noted above. In this intermediate range, the challenge is not only to describe coarse porous structures, but also to optimize flow elements and to assemble them. The resulting flow structures are designed porous media. The usual way of deriving the laws governing the macroscopic variables is to begin with the standard equations obeyed by the fluid and to obtain the macroscopic equations by averaging over volumes or areas containing many pores.

Applications of porous medium

Porous medium is involved in numerous applications covering a large number of engineering disciplines. Some of these applications are:

1. Combustion processes

2. Heat exchanger applications

3. Solar energy collectors

4. Refrigerators and recuperators

5. Insulation of buildings and other mechanical devices etc

6. Packed and circulating bed combustors and reactors.

7. Energy storage and conversion methods

8. Containment transport in groundwater and exploitation of geothermal resources.

9. Drying problems such as vegetable, grains, ceramic, wood, brick etc.

10. Flow through different organs of animal body for example lungs.

11. Problem involving nuclear energy such as heat removal from packed bed nuclear reactors, multishield structures used in the insulation of nuclear reactors, nuclear waste disposal etc.

Heat transfer in porous medium

The phenomenon of natural convection in an enclosure is as varied as the geometry and orientation of the enclosure. Judging from the number of potential engineering applications, the enclosure phenomena can be organized into two classes:

(1) Enclosures heated from the side.

(2) Enclosures heated from below. The fundamental difference between enclosures heated from the side and enclosures heated from below is that in enclosures heated from the side, a buoyancy-driven flow is present as soon as a very small temperature difference (Th−Tc) is imposed between the two sidewalls. By contrast, in enclosures heated from below, the imposed temperature difference must exceed a finite critical value before the first signs of fluid motion and convective heat transfer are detected. In this study, heat transfer by natural convection across porous mediafilled enclosure is considered. In such flow, in porous media there is a buoyancy-driven flow which is entirely enclosed by a solid wall along which differential heating is applied, the resulting temperature difference leading to the generation of buoyancy force which causes the flow. We find enclosures heated from the side in the cooling systems of industrial-scale rotating electric machinery. Enclosures heated from below refer to the functioning of thermal insulations oriented horizontally, for example, the heat transfer through a flat-roof attic space.

Radiation

Radiation heat transfer in the porous media plays an important role when natural convection is relatively small. It has been reported in literature that the radiation heat transfer has received little attention as compared to natural convection heat transfer. One reason for this is that the inclusion of radiation term in the governing energy equation of the porous medium increases the complexity of partial differential equations. But when we look at the realistic aspects of heat transfer, then it is seen that there are various applications wherein radiation heat transfer takes place and thus cannot be ignored. For instance the combustion processes, high temperature heat exchangers, solar energy collectors, the radiative drying of papers and other porous materials, manufacturing systems that use laser to melt the powder etc.

Stream Function, Heat Function and Nusselt Number

Stream Function:

The boundary conditions of Eq. (3.4 and 3.5) are $\psi = 0$ for all solid boundaries. Numerical results for streamlines and isotherms for natural convection were obtained for Ra numbers. Positive sign of ψ denotes anti-clockwise circulation and clockwise circulation is represented by negative sign of ψ.

Heat Function:

The heat flow within the enclosure is displayed using heat function (H) obtained from

conductive heat fluxes $\frac{}{X}$, $\frac{}{Y}$ as well as convective heat fluxes (Uθ, Vθ). The heatfunction satisfies the steady energy balance equation such that

$$\frac{H}{Y} \quad U \quad \frac{}{X}$$

$$\frac{H}{X} \quad V \quad \frac{}{Y}$$

which yields a single equation

$$\frac{^2 H}{X^2} \quad \frac{^2 H}{Y^2} \quad \frac{}{Y} U \quad \frac{}{X} V$$

The sign convention for heatfunction is as follows. The positive sign of H denotes anti-clockwise heat flow and clockwise heat flow is represented by negative sign of H. The value of heat function at the origin point is assumed as H(0,0)=0. Four vertices A,B,C,D of cavity.

At A, H=0 as it is origin point.

At B, H= $Nu_x \, dx$

0

At C, value of Heatfunction is same as at B since inclined wall is adiabatic At D, value of Heatfunction is same as at A since inclined wall is adiabatic

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Nusselt Number:

The local heat transfer coefficient is defined as $h_y = \frac{q''}{T_S \quad T_C}$ at a given point on the heat source surface, where T_S is the local temperature on the surface. Accordingly the local Nusselt number is obtained as $Nu_x = \frac{h_y x}{k}$. The trapezoidal rule is used for numerical integration to obtain the average Nusselt number.

In order to determine the local Nusselt number, the temperature profiles are fit with quadratic (three nodal points are considered near the wall), cubic and bi-quadratic polynomials and their gradients at the walls are determined. It has been observed that the temperature gradients at the surface are almost the same for all the polynomials considered. Hence only a quadratic fit is made for the temperature profiles to extract the local gradients at the walls to calculate the local heat transfer coefficients from which the local Nusselt numbers are obtained. Integrating the local Nusselt number over each side, the average Nusselt number for each side is obtained as

On bottom wall, $Nu_{avg} = {}^{1}_{0}\, Nu\, dX$

On top wall, $Nu_{avg} = \frac{1}{L_x 2 \; L_x} \, {}^{x_2}_{x} \, Nu\, dX$ where L_{x2} and L_{x1} represent the lengths of the cavity

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at vertices C and D respectively from the origin.

Conclusion

The contours of stream functions, isotherms and heatlines are symmetric about the central vertical line for uniform temperature when bottom wall is subjected to constant temperature and are not symmetric for linearly varying temperature and sinusoidal temperature cases. The heat transport from the hot to cold region inside porous trapezoidal enclosure is studied using heatline flow visualization technique. Nusselt number decreses with an increase the aspect ratio and increases with an increase of side wall inclination angle γ. Nusselt number increases monotonically with increase of Ra for both top and bottom walls and is more for uniform temperature than that of linearly and sinusoidally varying temperature cases for the hot and cold walls. Partition is a control parameter for flow field and temperature distribution. Location of partition becomes insignificant for low values of Rayleigh number. Heat transfer decreases with the length and when the solid wall is positioned away from bottom wall.

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