Frontiers in Heat and Mass Transfer (FHMT), 9, 24 (2017)
DOI: 10.5098/hmt.9.24

Global Digital Central
ISSN: 2151-8629

Frontiers in Heat and Mass Transfer

Available at www.ThermalFluidsCentral.org

CONJUGATE DOUBLE DIFFUSION IN A SQUARE CAVITY DIVIDED INTO TWO SECTIONS

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ABSTRACT

The current work discusses the heat and mass transfer due to a solid wall dividing the porous medium into two distinct sections. The left vertical surface of cavity is maintained at constant temperature T_h and concentration C_h whereas right vertical surface is kept at isothermal temperature T_c and iso-concentration C_c such that $T_h>T_c$ and $C_h>C_c$. Finite element method is used to solve the governing partial differential equations. The results discussed with respect to thermal conductivity ratio, solid width, buoyancy ratio, Lewis number etc.

Keywords: *Conjugate double diffusion, Porous Cavity, FEM*

1. INTRODUCTION

Heat transfer in porous medium is one of the well-studied and documented areas of research for many decades. The passage of time has brought in more applications of porous medium compelling researchers to look into those new emerging areas encompassing porous medium. The various applications and issues pertaining to porous medium is well discussed in some of the popular books such as (Ingham and Pop, 1998; Pop and Ingham, 2001; Nield and Bejan, 2006; Vafai, 2000; Bejan and Kraus, 2003). Natural convection in porous medium refers to a case where fluid gets heated due to temperature gradient at different points and moves to areas of lower temperature due to thermal buoyancy. Such studies have been reported for different geometrical and physical parameters of porous fluid combination (Quadir *et al.* 2016; Yunus Khan *et al.* 2016; Badruddin *et al.* 2007; Badruddin *et al.* 2006; Prasad *et al.* 1984; Ahmed *et al.* 2011; Badruddin *et al.* 2012; Zheng *et al.* 2001; Badruddin *et al.* 2006; Nik-Ghazali. *et al.* 2014).

The conjugate heat transfer in porous medium arises due to presence of a solid in the fluid flow path where the energy transfer is a complicated issue. Such phenomenon requires an additional equation to be considered for solid region with adequate boundary conditions that links the temperature at porous and solid region (Azeem *et al.* 2016; Ahmed *et al.* 2014; Badruddin *et al.* 2015; Sakakibara *et al.* 1987; Saeid, 2007; Abdallah Al-Amiri *et al.* 2008; Inna *et al.* 2010; Pop *et al.* 2000; Ahmet Kaya *et al.* 2011; Higuera and Pop, 1997). The conjugate heat transfer in porous medium is generally studied with respect to single diffusion or just heat transfer. However, there is not much information available for the case when double diffusion or heat and mass transfer occurs inside the porous medium with a solid wall dividing the domain. Most of the studies have addressed the conjugate heat transfer in terms of solid wall being placed at one end of the porous medium such as left of cavity (Saeid, 2007), bottom and top of cavity (Baytas *et al.* 2001) etc.

The current work is different from those available in literature in a way that the solid wall divides the porous cavity into two distinct regions. To the best of author's knowledge, double diffusion in a square porous medium separated by solid wall is not yet reported. Thus, it is an attempt to understand the double diffusion in such situation.

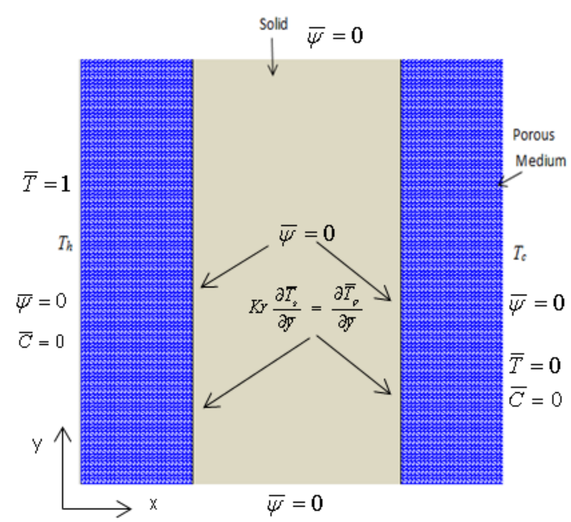

Fig. 1 Physical domain

2. MATHEMATICAL MODEL

Consider a square cavity having filled with saturated porous medium and a solid wall placed vertically at center of the cavity as illustrated in figure 1. The coordinates of domain are represented as x and y. The left vertical surface of cavity is maintained at higher temperature and concentration as compared to right vertical surface. The top and bottom surfaces of cavity are adiabatic. It is assumed that the Darcy law is applicable for porous cavity, the thermal equilibrium exists between fluid and solid phase of porous region, there is no phase change and the fluid properties are constant except the variation of density with temperature. The

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DOI: 10.5098/hmt.9.24 ISSN: 2151-8629

governing equations for above mentioned problem can be given in non-dimensional form as:

Momentum equation

$$\frac{\partial^2 \overline{\psi}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{\psi}}{\partial \overline{y}^2} = -Ra\left[\frac{\partial \overline{T}}{\partial \overline{x}} + N\frac{\partial \overline{C}}{\partial \overline{x}}\right] \quad (1)$$

Energy equation for porous region

$$\left[\frac{\partial \overline{\psi}}{\partial \overline{y}}\frac{\partial \overline{T}}{\partial \overline{x}} - \frac{\partial \overline{\psi}}{\partial \overline{x}}\frac{\partial \overline{T}}{\partial \overline{y}}\right] = \left(\left(1+\frac{4R_d}{3}\right)\frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{T}}{\partial \overline{y}^2}\right) \quad (2)$$

Energy equation in solid region

$$\left(1+\frac{4R_d}{3}\right)\frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{T}}{\partial \overline{y}^2} = 0$$

(3)

Concentration equation

$$\frac{\partial \overline{\psi}}{\partial \overline{y}}\frac{\partial \overline{C}}{\partial \overline{x}} - \frac{\partial \overline{\psi}}{\partial \overline{x}}\frac{\partial \overline{C}}{\partial \overline{y}} = \frac{1}{Le}\left(\frac{\partial^2 \overline{C}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{C}}{\partial \overline{y}^2}\right)$$

(4)

The dimensional details of above equations can be obtained from (Azeem *et al.* 2016)

The corresponding boundary conditions are

at $\overline{x} = 0 \quad \overline{\psi} = 0 \quad \overline{T} = 1 \quad \overline{C} = 1$ (5a)

at $\overline{x} = 1 \quad \overline{\psi} = 0 \quad \overline{T} = 0 \quad \overline{C} = 0$ (5b)

at $\overline{y} = 0 \quad and \quad \overline{y} = 1, \overline{\psi} = 0 \quad \frac{\partial \overline{T}}{\partial \overline{y}} = 0$ (5c)

at $\overline{y} = \overline{y}_{sp} \quad \overline{\psi} = 0 \quad Kr\frac{\partial \overline{T}_s}{\partial \overline{y}} = \frac{\partial \overline{T}_p}{\partial \overline{y}}$ (5d)

The following non-dimensional parameters are used

$$\overline{x} = \frac{x}{L} \quad \overline{y} = \frac{y}{L} \quad \overline{\psi} = \frac{\psi}{\alpha} \quad \overline{T} = \frac{(T - T_\infty)}{(T_w - T_\infty)} \quad (6)$$

$$R_d = \frac{4\sigma n^2 T_\infty^{\ 3}}{\beta_R k_s}, \quad Ra = \frac{g\beta_T \Delta TKL}{\nu\alpha}, Le = \frac{\alpha}{D},$$

$$N = \frac{\beta c(C_w - C_\infty)}{\beta_T (T_w - T_\infty)}$$

The Nusselt number and Sherwood number at hot surface can be calculated as:

$$Nu = -\left(\left(1+\frac{4}{3}R_d\right)\frac{\partial \overline{T}}{\partial \overline{x}}\right)_{\overline{x}=0} \quad (7)$$

$$Sh = \left(-\frac{\partial \overline{C}}{\partial \overline{x}}\right)_{\overline{x}=0} \quad (8)$$

The non-dimensional equations 1-4 are solved using finite element method with the help of 3-noded triangular elements. The application of finite element method resulted into large number of algebraic equations that are linked together thus they should be solved simultaneously. The algebraic equations are solved by assembling them into a global stiffness matrix subjected to boundary conditions 5. There are 4 equations which are coupled together thus they are solved in iterative manner by setting the tolerance limit of 10^{-7}, 10^{-5}, 10^{-5} as convergence criteria for $\overline{\psi}$, $\overline{T}$ *and* $\overline{C}$ which represents the non-dimensional stream function, temperature and concentration respectively. A total of 2592 elements are selected in the current study which produced the results as given in table 1. The higher number of elements (4232) tested did not give much variation in the results but consumed almost 600% increase in solution time as compared to 2592 elements. The accuracy of present method is verified by comparing the results available in open literature. The comparison is shown in table 1 that shows that the current method has good accuracy in predicting the Nusselt number. The results of table 1 corresponds to $S_w=0$ (solid width), $Le=1$(Lewis number) *and* $N=0$ (Buoyancy ratio).

Table 1: *Nu* Comparison of present method

Author	$Ra = 10$	$Ra = 100$
Present	1.0821	3.2126
Walker and Homsy (1978)		3.097
Bejan (1979)		4.2
Gross *et al.* (1986)		3.141
Monolo and Lage (1992)		3.118
Beckerman *et al.* (1986)		3.113
Moya *et al.* (1987)	1.065	2.801
Baytas and Pop (1999)	1.079	3.16
Misirlioglu *et al.* (2005)	1.119	3.05
Badruddin *et al.* (2012)	1.079	3.200
Badruddin *et al.* (2012	1.0798	3.2005

3. RESULTS AND DISCUSSION

The heat and mass transfer in porous medium can be best observed by having the information of temperature lines, concentration lines and streamline distribution due to applied boundary condition. Thus, isotherms, iso-concentration and streamlines are plotted for various physical and geometric parameters such as, thermal conductivity ratio, width ratio, Buoyancy ratio and Lewis number. Fig.2 shows isotherms, iso-concentration and streamlines distribution when thermal conductivity ratio varied from 0.1 to 25. The other parameters for this figure are kept at *Ra= 100* (Rayleigh number), *N=0.5, Le=5, Sw=13% and Rd=1*(Radiation parameter). The left column of Fig.2 belongs to *Kr=0.1*(Thermal conductivity ratio) and right column *Kr=25*. The conductivity ratio highlights the relative thermal conductivity of solid wall to that of porous medium. It is seen that the isotherms are very much clubbed together inside the solid wall when thermal conductivity ratio is low but spread out when *Kr* is high. The higher thermal conductivity ratio allows more thermal energy to be transferred across the solid wall thus increasing the thermal energy content of porous region on right side of cavity. The concentration lines indicate that the increased thermal conductivity ratio leads to increased concentration gradient at hot wall which is illustrated by iso-concentration lines moving to the left of cavity. The velocity of fluid increases when *Kr* is increased as indicated by increased value of streamline.

Fig.3 shows the effect of increasing the width of solid wall placed in porous medium. The left column corresponds to solid width S_w=13% and right column to 36% of cavity width. The other parameters are *Ra= 100, N=0.5, Le5, Kr=10 and Rd=1*. The increased solid width increases the thermal resistance of whole domain that in turn reduces the convection effect in the porous region which is reflected in terms of reduced value of isotherms on right side of cavity. It is noted that the isotherms are comparatively straighter at higher S_w indicating that the conduction effect increase with increase in width ratio. The concentration lines are confined to a smaller region due to increase in width ratio. The magnitude of streamlines on left side of solid wall increases slightly where as it decreases on right side of solid wall. This happens because of the reason that the thermal energy is concentrated largely on left side of cavity as compared to right side due to higher thermal resistance introduced by wider solid that leads to increased velocity on the left side of solid wall.

Fig.4 shows the effect of buoyancy ratio on the heat and mass transfer in porous cavity. This figure corresponds to *Ra= 100,* S_w*=13%, Le=5, Kr=10 and Rd=1*. The increase in buoyancy ratio makes the isotherms to move slightly away from hot surface on upper section of cavity but brings it closer at lower section. This indicates that the heat transfer rate should increase at lower section of cavity and decrease at upper section. Similar trend can be observed for concentration lines that reflect that the mass transfer increases at lower section of cavity. This is further vindicated by increase in the fluid velocity as shown by increased magnitude of stream function that helps in increasing the heat and mass transfer rate. One of the important parameter that affects the mass transfer rate in porous medium is Lewis number as demonstrated in fig.5 that corresponds to *Ra= 100,* S_w*=13%, N=0.5, Kr=10 and Rd=1*. The isotherms are not much affected due to increase in *Le* from 1 to 25. However, the iso-concentration lines have substantially changed in the left region of cavity due to increased Lewis number. The iso-concentration lines got pushed towards the hot surface at higher *Le* that should increase the concentration gradient.

The isotherms, iso-concentration lines are plotted to show the thermal energy and concentration distribution inside the domain. However, the important information regarding heat and mass transfer can be inferred from Nusselt and Sherwood number which is reflection of heat and mass transfer rate at the hot surface. The following section is dedicated to discuss the heat and mass transfer with respect to various geometrical and physical parameters. Fig.6 shows the local Nusselt and Sherwood number variation along the height of cavity due to variation in thermal conductivity ratio between the porous and solid wall of domain. This figure is obtained at *Ra= 100,* S_w*=13%, Le=5, N=0.5 and Rd=1.* The Nusselt and Sherwood number decreases along the height of cavity. This is a result of hot fluid getting heated at bottom section that moves towards upward direction taking along with itself the thermal energy and helping in mass diffusion. As the fluid moves upwards, its direction shifts towards the right side of cavity that in turn reduces the thermal and concentration gradient leading to reduced Nusselt and Sherwood number at upper portion. The increase in thermal conductivity ratio increases the heat and mass transfer. This can be easily inferred from isotherms and iso-concentration of fig 2 which tends to move towards the hot surface leading to increased thermal and concentration gradient due to increase in Kr. The heat transfer is affected to greater extent due to change in *Kr* as compared to mass transfer. Fig.7 corresponding to *Ra= 100, Kr=10, Le=5, N=0.5,* shows the influence of solid width ratio on the heat and mass transfer behavior. It is found that the Nusselt number slightly decreases at bottom section of cavity due to increase in the width ratio but increase at the top section of hot surface. This can be attributed to decreased fluid velocity caused by limited space for fluid movement as the region occupied by solid wall increases with increased width ratio. Reverse trend as that of Nusselt number is observed for mass transfer where Sherwood number increases with solid width ratio at bottom part but decreases slightly at top section. The decreased porous width due to increase in S_w leads to higher concentration gradient thus increasing the Sherwood number at bottom section

The effect of buoyancy ratio on heat and mass transfer is shown in Fig.8, which is obtained by keeping the parameters as *Ra= 100, Kr=10, Le=5,* S_w*=13%.* The Nusselt and Sherwood number increases with increase in buoyancy ratio at bottom of cavity due to the fact that the positive value of *N* results into assisting flow when the thermal buoyancy and concentration buoyancy assist each other thus increasing the heat and mass transfer. However, the effect of buoyancy ratio diminishes as the height of cavity increases as indicated by merged lines for various values of *N*. Lewis number affects the mass transfer significantly as compared to heat transfer as illustrated by fig.9 corresponding to the parameters *Ra= 100, Kr=10, N=0.5,* S_w*=13%.* The mass transfer rate drops sharply from lower part until about 10% of cavity height from bottom and then decreases gradually due to increased concentration gradient at lower section of cavity as corroborated by iso-concentration lines of fig 5. The mass transfer rate is higher for higher Lewis number for any given height of cavity. The Nusselt number decreases slightly with increase in Lewis number which is further vindicated by straightened isotherms (Fig.5) at higher Lewis number.

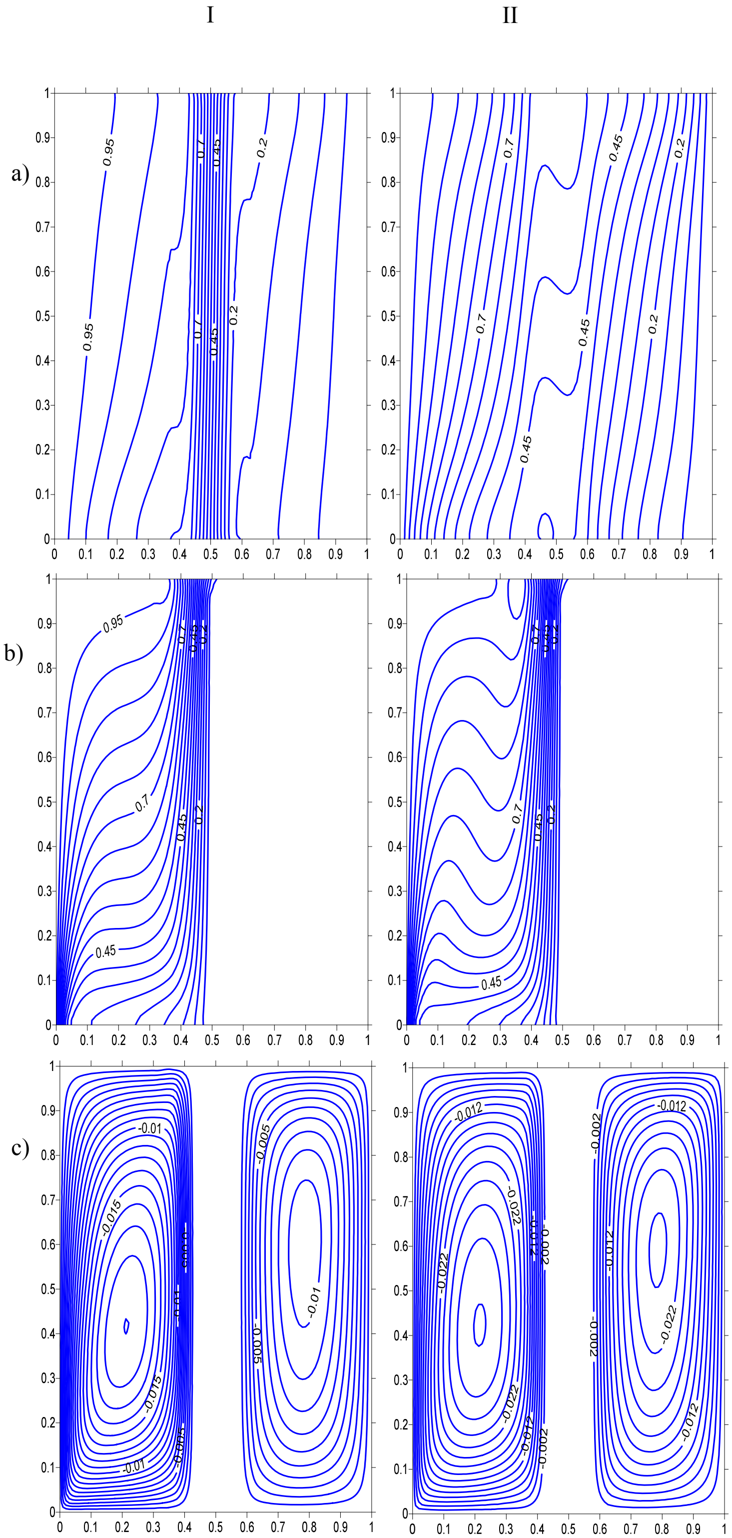

Fig. 2 Effect of Thermal Conductivity Ratio I) *Kr = 0.1* II) *Kr = 25*
a) Isotherms b) Iso-concentration c) Streamlines

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ISSN: 2151-8629

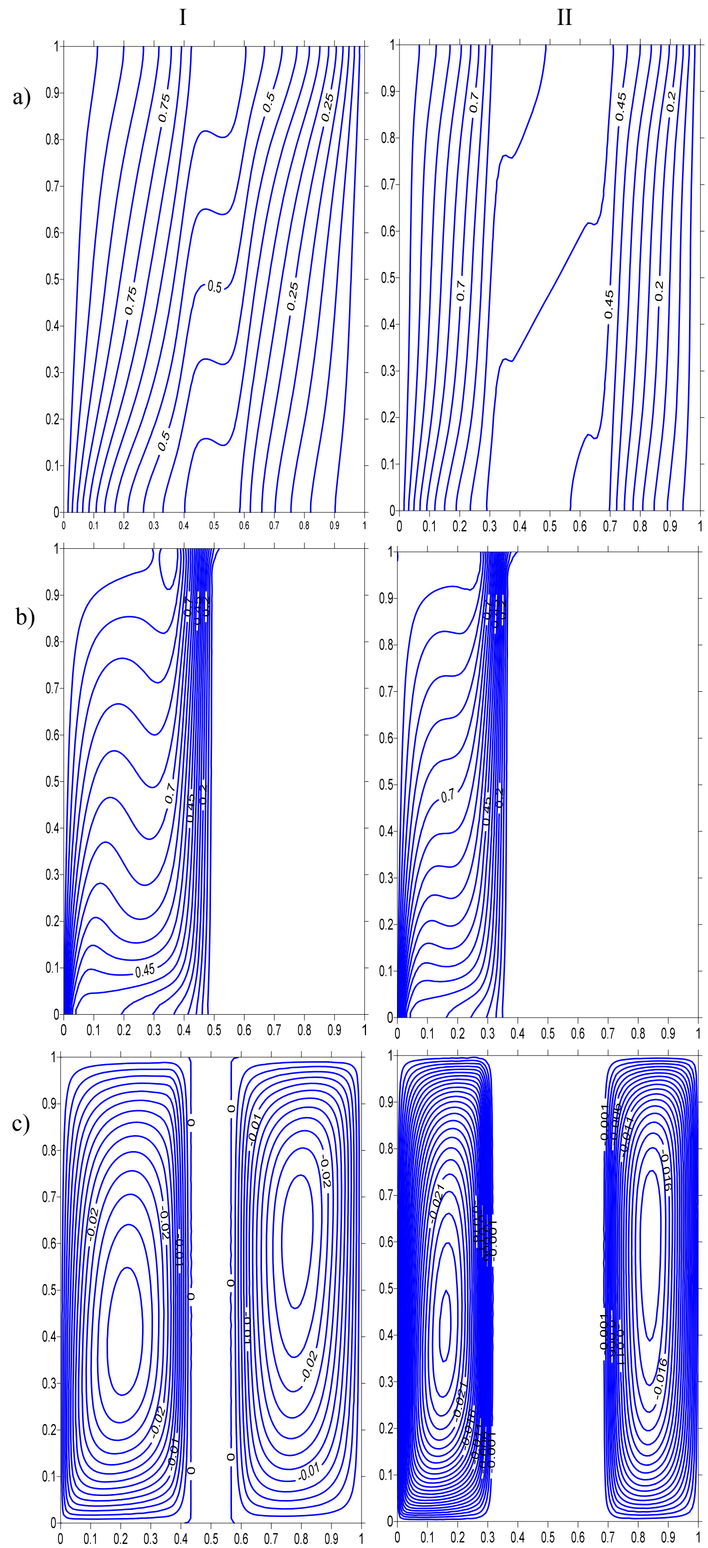

Fig. 3 Effect of Solid Width Ratio I) $S_w = 13\%$ II) $S_w=36\%$
a) Isotherms b) Iso-concentration c) Streamlines

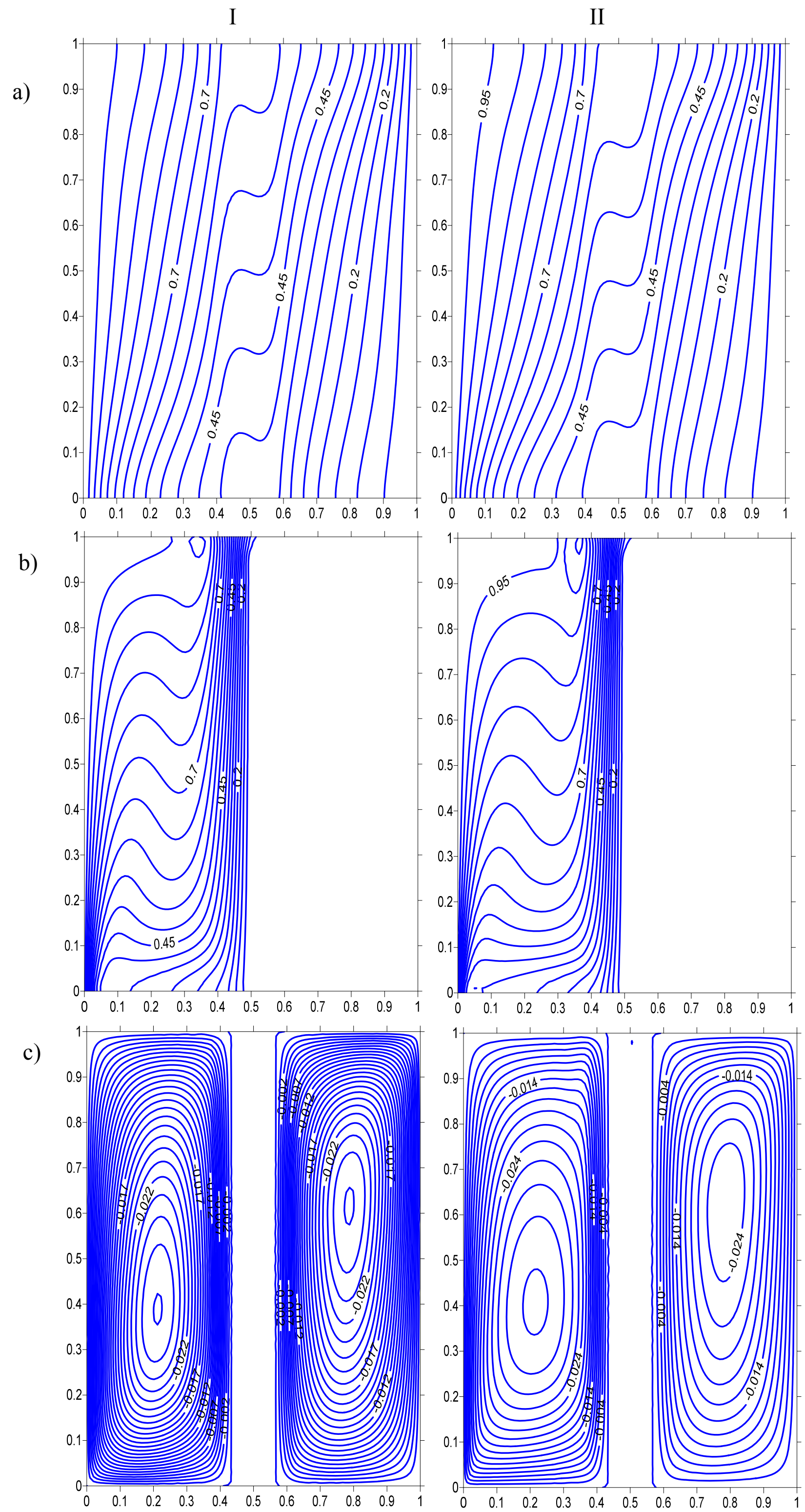

Fig. 4 Effect of Buoyancy Ratio I) $N = 0.1$ II) $N=1$
a) Isotherms b) Iso-concentration c) Streamlines

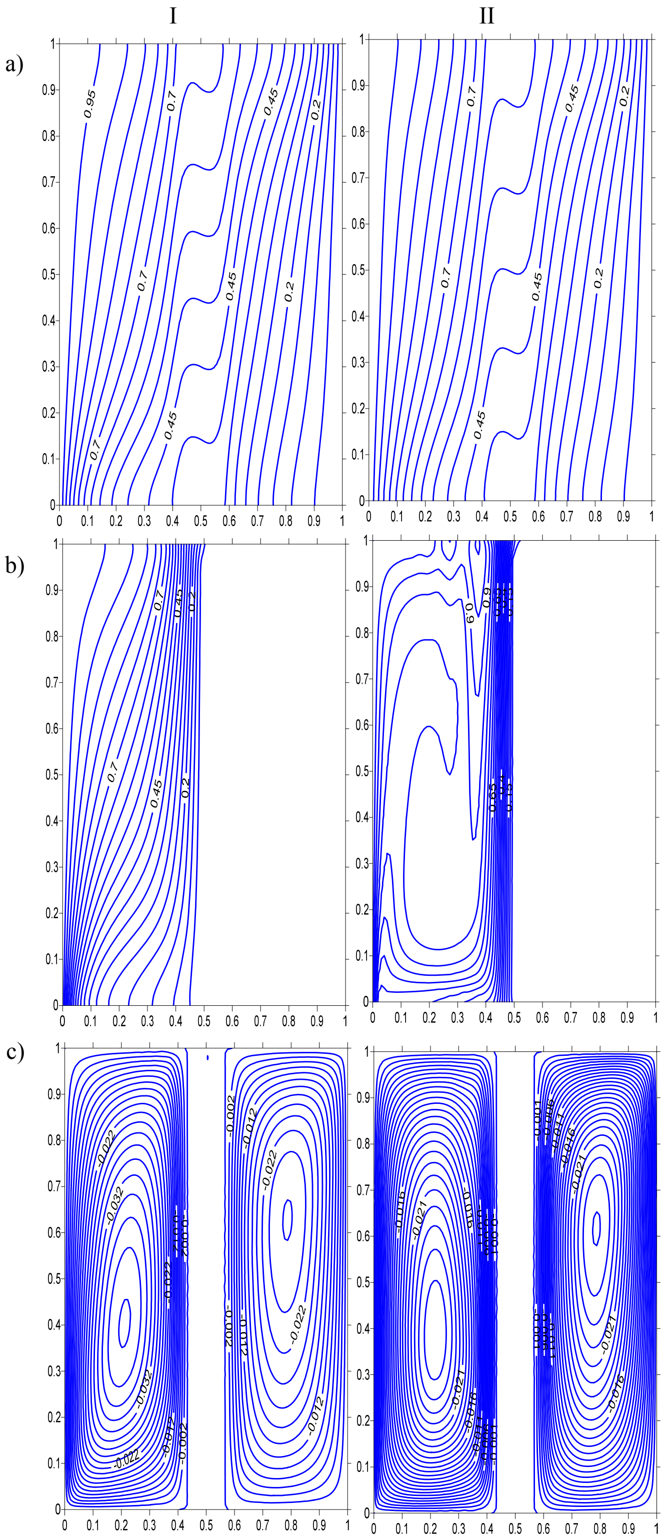

Fig. 5 Effect of Lewis Number I) *Le= 1* II) *Le=25*
a) Isotherms b) Iso-concentration c) Streamlines

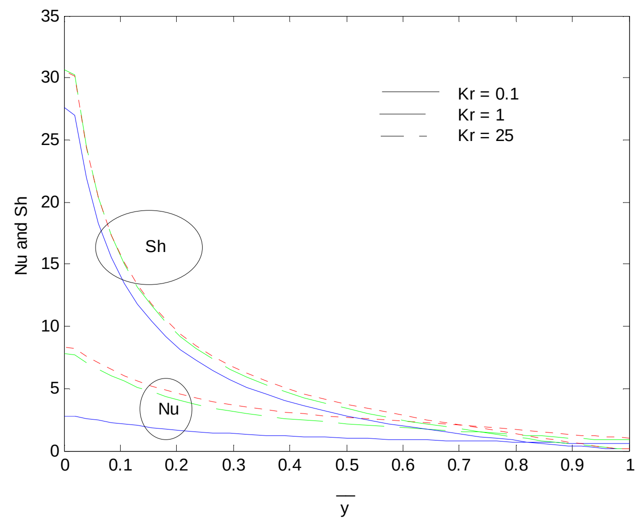

Fig. 6 Local Nusselt and Sherwood number variation with respect to Kr

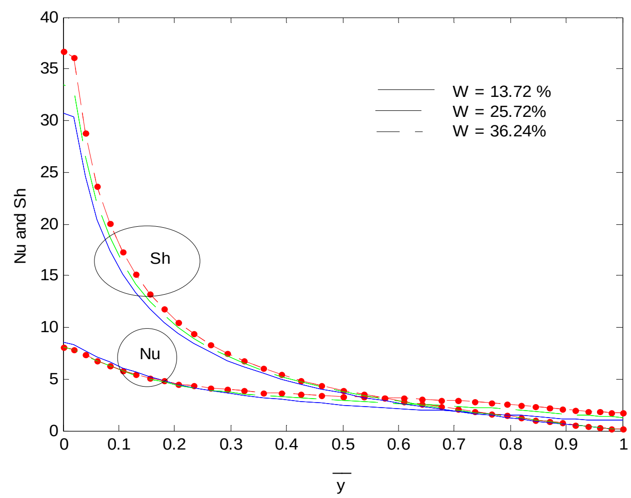

Fig. 7 Local Nusselt and Sherwood number variation with respect to S_w

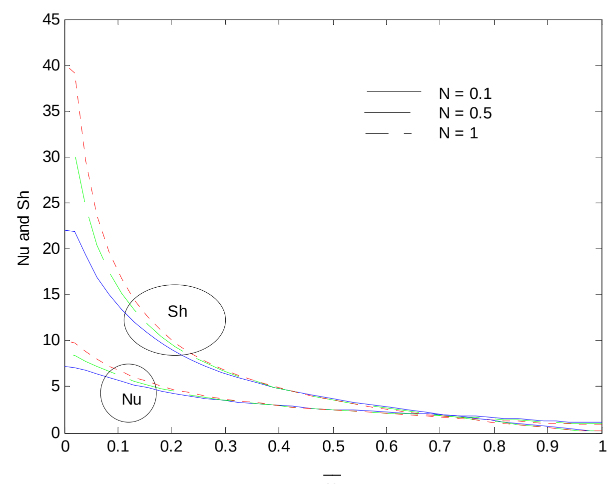

Fig. 8 Local Nusselt and Sherwood number variation with respect to N

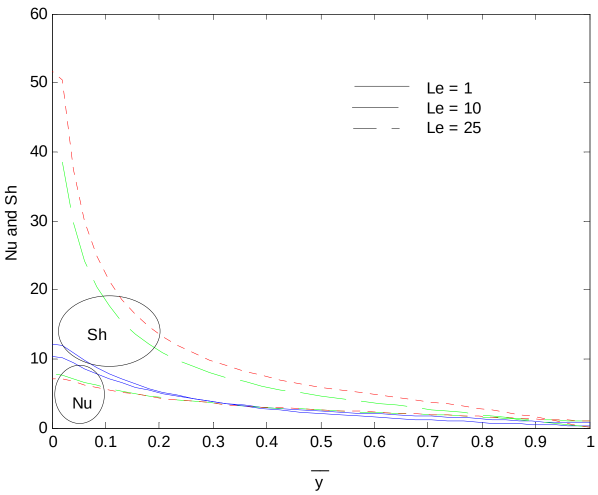

Fig. 9 Local Nusselt and Sherwood number variation with respect to Le

4. CONCLUSION

The aim of this article is to investigate the heat and mass transfer characteristics in a square porous cavity having a solid wall placed at the center that divides the porous medium into two regions. Finite element method is used to solve the governing partial differential equations. The results discussed could help in the drying process such as different types of grains being segregated by a solid separator between them. Following conclusion is drawn from current study

- The heat and mass transfer increases with increase in conductivity ratio
- The Nusselt number slightly decreases at bottom section of cavity due to increase in the width ratio but increase at the top section. However, the reverse trend is observed for mass transfer.
- The Nusselt and Sherwood number increases with increase in buoyancy ratio at bottom of cavity.
- Mass transfer is affected to greater extent due to change in Lewis number.

NOMENCLATURE

$\overline{C}$	Species concentration
D	Mass diffusivity
g	Acceleration due to gravity (m/s^2)
k_p ,k_s	Porous and Solid thermal conductivity respectively (W/m-^{o}C)
K	Permeability of porous medium (m^2)
Kr	Conductivity ratio
L	Height and length of cavity (m)
Le	Lewis number
Nu	Nusselt number
N	Buoyancy ratio
q_r	Radiation flux (W/m^2)
R_d	Radiation parameter
Ra	Modified Raleigh number
Sh	Sherwood number
S_w	Solid width
$\overline{T}$	Temperature
$\overline{x}$, $\overline{y}$	Non-dimensional co-ordinates

Greek Symbols

α	Thermal diffusivity (m^2/s)
β_C	Coefficient of concentration expansion
β_T	Coefficient of thermal expansion
β_R	Absorption coefficient (1/m)
ρ	Density (kg/m^3)
v	Coefficient of kinematic viscosity(m^2/s)
σ	Stephan Boltzmann constant (W/m^2-K^4)
$\overline{\psi}$	Non-dimensional stream function

Subscripts

h	Hot
c	Cold
p	Porous
s	Solid

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