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Double Diffusive Convection and the Improvement of Flow in Square Porous Annulus

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ABSTRACT
There has been increased interest shown in recent years to investigate the behavior of heat and mass transfer in a square annulus with a porous medium fixed between the inner and outer walls. This paper aims to evaluate the Soret effect arising in the case of heat and mass transfer in a porous medium bounded by a square annulus and subjected to isothermal heating of the inner surfaces as well as the outer horizontal surfaces. The phenomenon is governed by 3 partial differential equations, the momentum, energy and concentration equations, that are coupled together and result in a situation where change in one variable affects the other equations and vice versa. The partial differential equations are converted into finite element equations with the help of the Galerkin method and then solved to predict solution variables such as temperature, stream function and concentration in the porous medium. It is found that the heat transfer rate at the hot wall decreases with increasing viscous dissipation effect in the porous medium.
Keywords – Porous media, Soret effect, aiding flow, FEM.

I. INTRODUCTION

This research focused on heat transfer by conduction and have considered convection only to the extent that it provides a possible boundary condition for conduction problem. The significance of heat and mass transfer phenomena is evident in the recent literature, demonstrating the wide range of applications in engineering science and research. The fundamental research pertaining to the various aspects of the transport of fluid with emphasis on the various modes of transport is well documented in the literature [1-5]. Heat and mass transfer in a porous medium is an important area of study because of its varied applicability across many fields, including: geothermal heat extractions, heat removal from nuclear reactors, heat exchangers, electronic components, solar energy storage technology, exothermic reactions in packed bed reactors, storage of grains, food processing, high performance insulation for energy efficient buildings and the spread of pollutants underground. The concept of convective heat transfer and fluid flow analysis for different geometries has been presented by many researchers over the last few years [6-30]. The emphasis on the study of natural convection [6-18], combined radiation and natural convection [19], conjugate heat transfer [20-22], and the thermal non-equilibrium approach to investigating heat transfer and fluid flow behavior [23-27] have been reported. In addition to the above, heat and mass transfer [28-29] and heat transfer in square cavities are also discussed in detail [30-42]. Viscous dissipation is an interesting phenomenon that arises due to friction between the moving fluid and the solid matrix of the porous medium. The viscous dissipation is known to decrease the heat transfer rate at the hot surface of a porous medium [16-17, 43]. The thermal-diffusion effect, which is known as the Soret effect, is an important factor that can significantly affect the flow field, especially in combined heat and mass transfer analyses. The Soret effect is the diffusion of mass due to the existence of a thermal gradient in the medium. The recent literature sheds more light on the various aspects of the Soret effect in cavities [44-47]. It has been observed that the rate of heat transfer increases with the Soret parameter [48] for a rectangular cavity subjected to an inclined magnetic field. There are various combinations of parameters, such as the magnetic field, inclination angle, and separation parameter that strongly influence heat and mass transfer inside the enclosure [49]. The present paper concentrates on the study of heat and mass transfer by considering the influence of the Soret effect on a flow in a square porous annulus subjected to isothermal heating of 6 surfaces. This is an extension of previous work [50-51] where only opposing flow was considered for a few parameters. The current work considers how to improve flow with a different set of boundary conditions. The geometry is found in applications as air conditioning supply systems where conditioned air is supplied through a square annulus. To the best of the authors' knowledge, this case has not been investigated so far.

II. MATHEMATICAL MODEL

A square porous annulus with 4 inner and 4 outer surfaces, as shown in Fig. 1, is considered where the porous medium is sandwiched between the inner and outer surfaces. The horizontal and vertical directions are represented by x and y axes respectively. The square annulus has an inner dimension of D which represents the hollow section of the annulus, or area without porous medium. It has an outer dimension of *LxL* where *L* represents the height or width of the annulus. The porous medium is subjected to isothermal heating at temperature T_h of the inner surfaces as well as of the outer horizontal surfaces. The outer vertical surfaces are kept at low temperature T_c. The outer surfaces have higher mass concentration C_h as compared to the inner surfaces C_c.

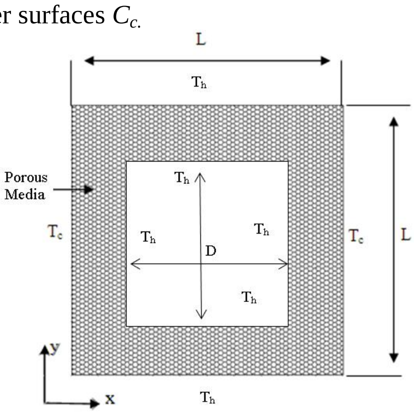

Fig. 1: Schematic of Porous Annulus

The following assumptions are applied

- The Darcy law is applicable
- There is no phase change in the fluid
- Thermal equilibrium exists between solid and fluid
- The properties of the fluid and those of the porous medium are homogeneous and isotropic
- Fluid properties are constant except the variation of density with temperature

In view of the above assumptions, the governing equations can be written as

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

Momentum equation

$$\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}=-\frac{g\beta K}{\nu}\frac{\partial T}{\partial x} \qquad (2)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial x} \qquad (3)$$

Concentration equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \qquad (4)$$

The applied boundary conditions are:

$$x=0,\ u=0,\ v=0,\ T=T_c \quad C=C_h \qquad (5a)$$

$$x=L,\ u=0,\ v=0,\ T=T_c \quad C=C_h \qquad (5b)$$

$$y=0,\ u=0,\ v=0,\ T=T_h \quad C=C_h \qquad (5c)$$

$$y=L,\ u=0,\ v=0,\ T=T_h \quad C=C_h \qquad (5d)$$

$$\frac{L-D}{2}\le x\le\frac{L+D}{2},\ y=\frac{L-D}{2},\ u=0,\ v=0,$$
$$T=T_h \quad C=C_c \qquad (5e)$$

$$\frac{L-D}{2}\le x\le\frac{L+D}{2},\ y=\frac{L+D}{2},\ u=0,\ v=0,$$
$$T=T_h \quad C=C_c \qquad (5f)$$

$$\frac{L-D}{2}\le y\le\frac{L+D}{2},\ x=\frac{L-D}{2},\ u=0,\ v=0,$$
$$T=T_h \quad C=C_c$$
(5g)

$$\frac{L-D}{2}\le y\le\frac{L+D}{2},\ x=\frac{L+D}{2},\ u=0,\ v=0,$$
$$T=T_h \quad C=C_c \qquad (5h)$$

The continuity equation (1) is satisfied by taking the stream function ψ as:

$$u=\frac{\partial\psi}{\partial y} \qquad v=-\frac{\partial\psi}{\partial x} \qquad (6)$$

The following non-dimensional parameters are used.

Non-dimensional width

$$\bar{x}=\frac{x}{L}$$

Non-dimensional height $\bar{y}=\frac{y}{L}$

Non-dimensional stream function

$$\bar{\psi}=\frac{\psi}{\alpha} \qquad (7)$$

Non-dimensional temperature

$$\bar{T}=\frac{(T-T_c)}{(T_h-T_c)}$$

Non-dimensional concentration

$$\bar{C}=\frac{(C-C_c)}{(C_w-C_c)}$$

Radiation parameter

$$R_d=\frac{4\sigma T_c^{\,3}}{\beta_r k}$$

Lewis number $Le = \frac{\alpha}{D_m}$

Buoyancy ratio

$$N = \left(\frac{\beta_c \Delta C}{\beta_T \Delta T} \right)$$

Soret parameter

$$Sr = \frac{D_m k_t (C - C_c)}{\alpha T_m (C_w - C_c)}$$

Rayleigh Number

$$Ra = \frac{g \beta \Delta T K L}{\nu \alpha}$$

Radiation can be approximated with the help of the Rosseland approximation as:

$$q_r = -\frac{4\sigma}{3\beta_r} \frac{\partial T^4}{\partial x} \quad (8)$$

Expanding T^4 in the Taylor series about T_c and neglecting higher order terms [6-7,18-19]

$$T^4 \approx 4TT_c^3 - 3T_c^4 \quad (9)$$

The substitution of the above non-dimensional parameters leads to:

Momentum equation

$$\frac{\partial^2 \overline{\psi}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{\psi}}{\partial \overline{y}^2} = -Ra \left[\frac{\partial \overline{T}}{\partial \overline{x}} + N \frac{\partial \overline{C}}{\partial \overline{x}} \right] \quad (10)$$

Energy equation

$$\frac{\partial \overline{\psi}}{\partial \overline{y}} \frac{\partial \overline{T}}{\partial \overline{x}} - \frac{\partial \overline{\psi}}{\partial \overline{x}} \frac{\partial \overline{T}}{\partial \overline{y}} = \left(\left(1 + \frac{4R_d}{3} \right) \frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{T}}{\partial \overline{y}^2} \right) \quad (11)$$

Concentration equation

$$\frac{\partial \overline{\psi}}{\partial \overline{y}} \frac{\partial \overline{C}}{\partial \overline{x}} - \frac{\partial \overline{\psi}}{\partial \overline{x}} \frac{\partial \overline{C}}{\partial \overline{y}} = \frac{1}{Le} \left(\frac{\partial^2 \overline{C}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{C}}{\partial \overline{y}^2} \right) + Sr \left(\frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{T}}{\partial \overline{y}^2} \right) \quad (12)$$

The corresponding boundary conditions in non-dimensional form are:

$\overline{x} = 0, \overline{\psi} = 0, \overline{T} = 0 \quad \overline{C} = 1$

$\overline{x} = 1, \overline{\psi} = 0, \overline{T} = 0 \quad \overline{C} = 1$

$\overline{y} = 0, \overline{\psi} = 0, \overline{T} = 1 \quad \overline{C} = 1$

$\overline{y} = 1, \overline{\psi} = 0, \overline{T} = 1 \quad \overline{C} = 1$

$\frac{1-W}{2} \le \overline{x} \le \frac{1+W}{2}, \overline{y} = \frac{1-W}{2}, \overline{\psi} = 0 \; \overline{T} = 1$

$\overline{C} = 0$ (13)

$\frac{1-W}{2} \le \overline{x} \le \frac{1+W}{2}, \overline{y} = \frac{1+W}{2}, \quad \overline{\psi} = 0 \; \overline{T} = 1$

$\overline{C} = 0 \; \frac{1-W}{2} \le \overline{y} \le \frac{1+W}{2}, \overline{x} = \frac{1-W}{2}, \overline{\psi} = 0 \; \overline{T} = 1$

$\overline{C} = 0 \; \frac{1-W}{2} \le \overline{y} \le \frac{1+W}{2}, \overline{x} = \frac{1+W}{2}, \overline{\psi} = 0 \; \overline{T} = 1$

$\overline{C} = 0$

Where $W = D/L$

The Nusselt number is expressed as follows:

At vertical surfaces

$$Nu = -\left[\left(1 + \frac{4Rd}{3} \right) \frac{\partial \overline{T}}{\partial \overline{x}} \right]_{T=T_h} \quad (14a)$$

At horizontal surfaces

$$Nu = -\left[\frac{\partial \overline{T}}{\partial \overline{y}} \right]_{T=T_h}$$

(15b)

III. RESULTS AND DISCUSSION

The governing equations (10-12), subjected to boundary conditions 13, make the problem under investigation a complex task to solve. Thus, the current methodology involves converting the partial differential equations into finite element equations with the help of the Galerkin method. Triangular elements are considered for converting the partial differential equations into algebraic equations. The application of the Galerkin method results in a set of multiple equations for each of equations (10-12). The finite element equations are assembled into a global matrix and solved iteratively to obtain the solution variables such as $\overline{T}, \overline{C}, \overline{\psi}$. The domain was meshed with 2040 triangular elements. The mesh density did not show significant variations with a higher number of elements thus 2040 elements were sufficient to model the problem under investigation. The current methodology was verified for its accuracy by comparing the results with previously published data as shown in Table I. It is clear from Table I that the current methodology is sufficiently accurate.

Fig. 2 shows the effect of D, which is the hollow section of the whole domain, or the area without the porous medium. This figure is obtained for

$Ra = 100, \; N = 0.5, \; Le = 2, \; Rd = 1, Sr = 0.5, \; \varepsilon = 0.005$.

An increase in D leads to less temperature variations in the porous medium as compared to that of smaller D as indicated by just two isotherms at the top and bottom of the square annulus. It is interesting to note that the temperature in the annulus is almost symmetrical about a horizontal central line. The mass concentration is high in the bottom region of the annulus when D is small but the concentration variation increases with increasing D. It is also noticeable that the concentration gradient is highest at the middle of the bottom line and almost constant along the left, right and top surfaces.

Table I: Comparison of Current Method for Average Nusselt Number $\overline{Nu}$ at $D = 0, R_d = 0, N = 0, Le = 1$

Author	Ra=10	Ra=100
Walker and Homsy [52]		3.097
Bejan [53]		4.2
Beckerman et al. [54]		3.113
Moya et al. [55]	1.065	2.801
Baytas and Pop [56]	1.079	3.16
Misirlioglu et al. [57]	1.119	3.05
Gross et al. [58]		3.141
Monolo and Lage [59]		3.118
Present	1.0798	3.2005

Fig. 3 shows the variation in the buoyancy ratio at $Ra = 100, D = 25\%, Le = 2, Rd = 1, Sr = 0.5$. The increase in N indicates the increase in concentration buoyancy as compared to thermal buoyancy. It is seen that the thermal gradient increases at the top section of the annulus with increasing N. It is also noted that the increase in N leads to a greater concentration gradient across the annulus surfaces thus leading to increased mass transfer rate. The fluid flow divides into 4 cells of circulation when the buoyancy ratio is increased.

Fig. 4 shows the variation in the Lewis number at $Ra = 100, D = 25\%, Rd = 0.5, Sr = 0.5, N = 0.2$. The Lewis number is the ratio of the thermal diffusivity to the concentration diffusivity. Le>1 indicates that the thermal diffusivity is higher than the concentration diffusivity, and vice versa for Le<1. It can be seen from the isotherms that the temperature lines spread deep into the porous region due to the increase in the Lewis number. However, the major impact of the Lewis number is observed in the concentration lines, which become distorted to a greater extent when the Lewis number is increased from 2 to 10. The fluid flow seems to skew towards the vertical direction due to an increase in the Lewis number.

Fig. 5 illustrates the effect of the Soret parameter for the case of $Ra = 100, D = 25\%, Le = 2, Rd = 1, N = 0.2$. It was found that the thermal behavior of the porous medium is not much affected due to change in Soret parameter, however, the concentration distribution is affected to a greater extent as illustrated by the iso-concentration lines. It was found that the concentration gradient decreases with an increase in the Soret parameter.

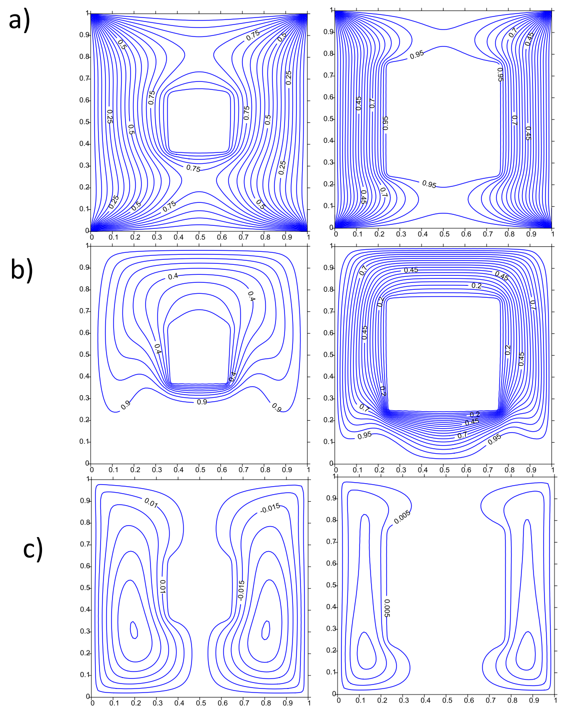

Fig. 2: I) *D* = 25%, II) *D* = 50%
a) Isotherms b) Iso-concentration c) Streamlines

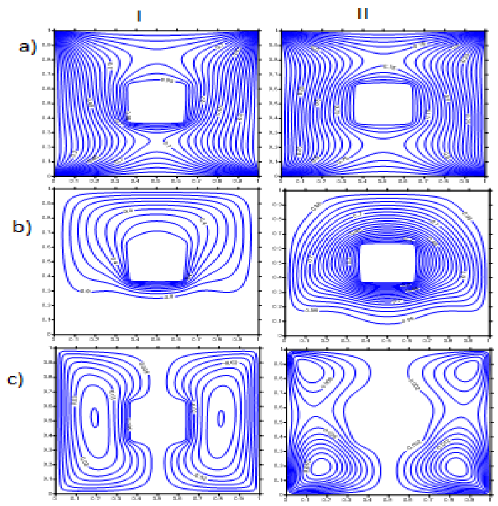

Fig. 3: I) *N* = 0.1, II) *N* = 1
a) Isotherms b) Iso-concentration c) Streamlines

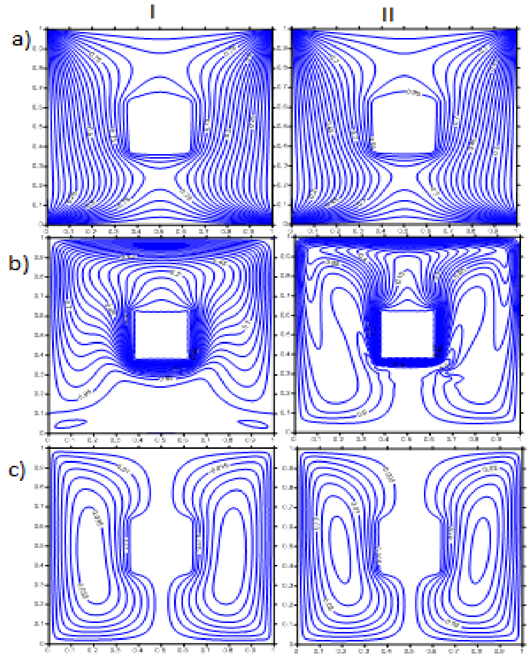

Fig. 4: I) $Le = 2$, II) $Le = 10$
a) Isotherms b) Iso-concentration c) Streamlines

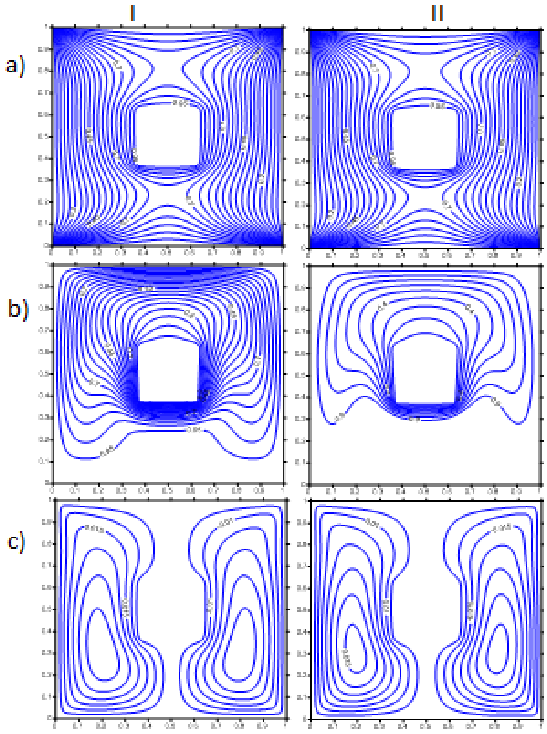

Fig. 5: I) $Sr = 0.1$, II) $Sr = 1$
a) Isotherms b) Iso-concentration c) Streamlines

Heat transfer analysis

The following section explains the heat transfer behavior of a square cavity in terms of the Nusselt number at 2 outer and 4 inner hot walls of the cavity. Fig. 6 shows the local Nusselt number variation along the hot walls for D = 0.25. It should be noted that the left and right walls behave similarly with respect to Nusselt number variation thus the lines representing them overlap each other resulting in only 3 lines for the inner walls of the annulus. It is noted that the Nusselt number of the top wall is lower than that of the other hot walls. This is because the fluid at the top wall loses its momentum after striking the wall thus reducing the convection of fluid as well as heat transfer from the top wall to the porous medium. The Nusselt number at the vertical walls is the highest among all of the walls. The fluid near the vertical walls is heated and moves in an upward direction due to buoyancy thus giving maximum opportunity to carry the heat. The bottom hot wall has a higher Nusselt number than the top wall but lower than that of the side walls.

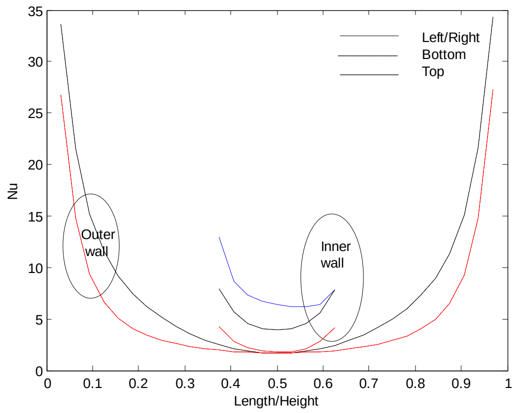

Fig. 6: Local Nu at *Ra=100, N=0.5, Le=2, R_d=1, Sr=0.5, D=0.25*

Fig. 7 shows the heat transfer behavior for the case when D is increased to 50% of the cavity length/height. It is noted that the Nusselt number for most of the inner vertical surfaces remains constant when D is increased from 0.25 to 0.5. The difference between the Nusselt number at the top and bottom inner walls decreases. This is because fluid in the vicinity of the top and bottom walls has less space in which to move due to the reduced porous medium when D is increased. This reduces the heat transfer rate at the top and bottom walls.

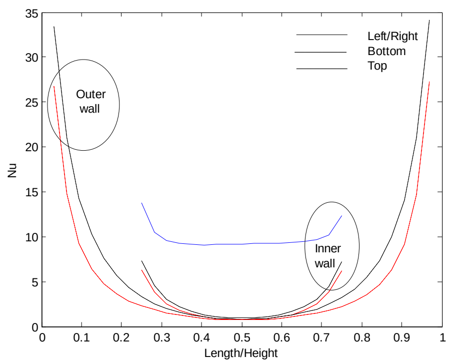

Fig. 7: Local Nu at *Ra=100, N=0.5, Le=2,* R_d*=1, Sr=0.5, D=0.5*

Figs. 8 and 9 show the effect of the Lewis number on the local Nusselt number at 6 hot surfaces of the annulus. As in other cases, the Nusselt number of the vertical wall is higher than that of other surfaces. The Nusselt number at the left/right and bottom walls increases marginally with increasing Lewis number. However, the Nusselt number at the top wall decreases marginally. The Nusselt number at the top outer wall is almost constant for most of the surface.

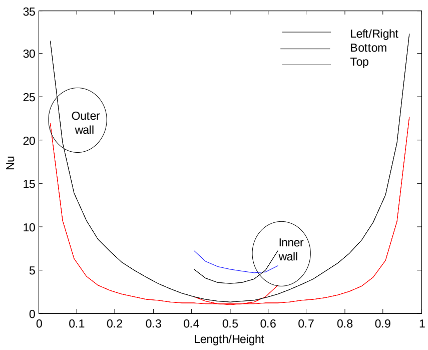

Fig. 8: Local Nu at *Ra=100, N=0.2, Le=2,* R_d*=0.5, Sr=0.5, D=0.25*

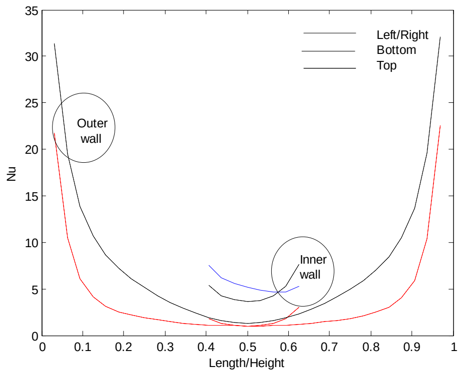

Fig. 9: Local Nu at *Ra=100, N=0.2, Le=10,* R_d*=0.5, Sr=0.5, D=0.25*

Figs. 10 and 11 illustrate the effect of the buoyancy ratio on the heat transfer characteristics of a square annulus. The buoyancy ratio (N) basically highlights the ratio of the concentration buoyancy to the thermal buoyancy. It is observed that the Nusselt number of the left and bottom inner walls is higher than that of the top inner wall for N=0.1. However, it is interesting to see that the local Nusselt number at the top inner wall is higher than that of the bottom inner wall for the case where N=1 (Fig. 11). This happens because the increased buoyancy ratio splits the fluid into 4 circulation regions that in turn results in an increase in the thermal gradient at the top surface as can be observed from the isotherms shown in Fig. 3. It is further observed that the Nusselt number at the left inner wall increases along all of the wall when N=1 (Fig. 11) whereas it decreases for most of the wall for N=0.1 (Fig. 10).

Figs. 12 and 13 show the effect of the Soret parameter on heat transfer behaviour for *Ra=100, N=0.5, Le=2,* R_d*=1, D=0.25.* The Soret effect is an effect where the existence of a temperature gradient leads to mass diffusion. Thus, it has more impact on mass transfer than on heat transfer. However, an increased Soret parameter slightly reduces the Nusselt number variations along the inner hot surfaces, as can be seen from a comparison of Figs. 12 and 13.

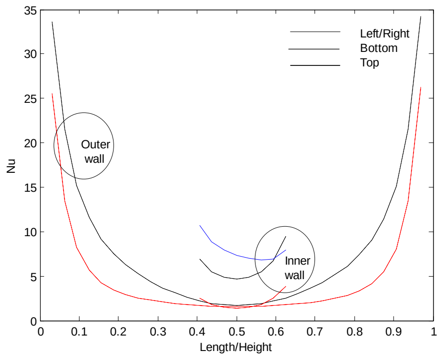

Fig. 10: Local Nu at *Ra=100, N=0.1, Le=1,* R_d*=1, Sr=0.5, D=0.25*

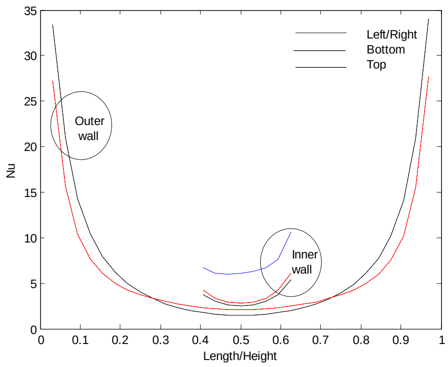

Fig. 11: Local Nu at *Ra=100, N=1, Le=1,* R_d*=1, Sr=0.5, D=0.25*

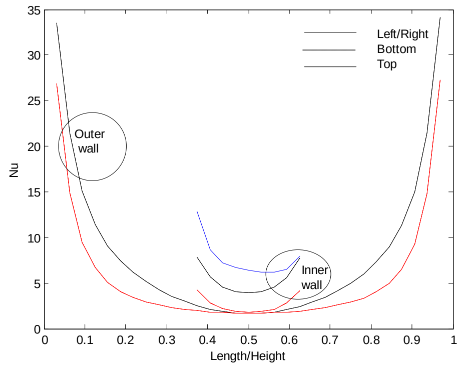

Fig. 12: Local Nu at *Ra=100, N=0.5, Le=2,* R_d*=1, Sr=0.1, D=0.25*

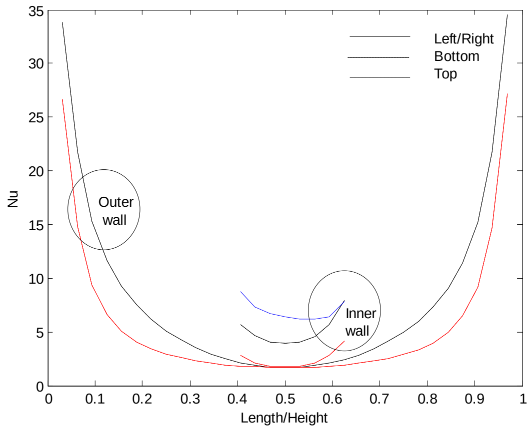

Fig. 13: Local Nu at *Ra=100, N=0.5, Le=2, R_d=1, Sr=1, D=0.25*

A. *Mass transfer*

The following section explains the mass transfer behavior of a square porous annulus. Mass transfer is described in terms of the Sherwood number. It can be seen that the mass transfer rate near the corners is substantially different from that of other sections of the high concentration walls and this is true for all 4 walls. It is worth mentioning that the left and right walls behave similarly in terms of mass transfer thus only one line is shown for two vertical walls. Figs. 14 and 15 show the effect of changing D on the mass transfer of a square annulus. It is seen that the Sherwood number of the top wall is higher than that of other walls and that that of the bottom wall is the lowest among the 4 outside walls. The Sherwood number of the top and vertical walls outside the vicinity of the annulus corners increases towards the center of the annulus and then decreases. However, the Sherwood number of the bottom wall increases sharply near the corners and then declines towards the center of the annulus, after which it further increases and finally falls away sharply. The increase in D substantially affects the mass transfer at the outer walls. The Sherwood number at the top wall is almost constant across D, whereas it sharply increases and decreases at the left and right sections of the annulus outside the length of the inner wall. It is interesting to note that the Sherwood number varies in a sinusoidal form at the bottom wall for D=0.5 whereas the mass transfer at the vertical walls is skewed towards the right wall.

Figs. 16 and 17 show the effect of the Lewis number on the mass transfer behavior of an annulus. It can be seen that an increase in the Lewis number increases the Sherwood number at the left/right or top walls. However, the increased Lewis number reduces the Sherwood number at the bottom wall. This is vindicated by large variations in concentration profile for *Le=2* and *Le=10*, as shown in Fig. 4, highlighting an increased concentration gradient at the left/right and top walls. The increased *Le* leads to a fluctuating Sherwood number at the bottom wall.

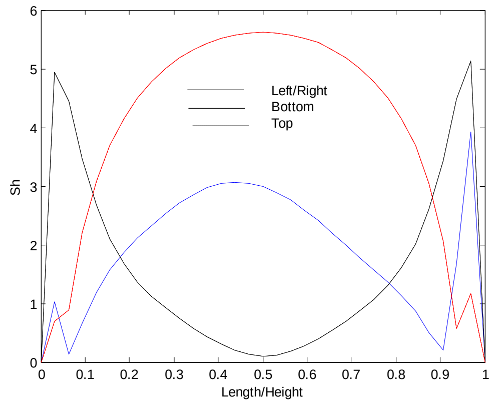

Fig. 14: Local *Sh* at *Ra=100, N=0.5, Le=2, R_d=1, Sr=0.5, D=0.25*

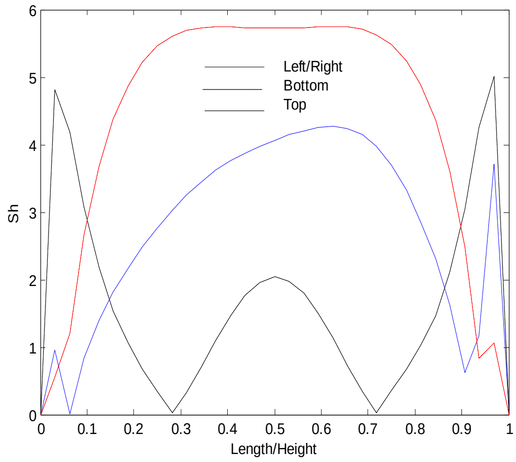

Fig. 15: Local *Sh* at *Ra=100, N=0.5, Le=2, R_d=1, Sr=0.5, D=0.5*

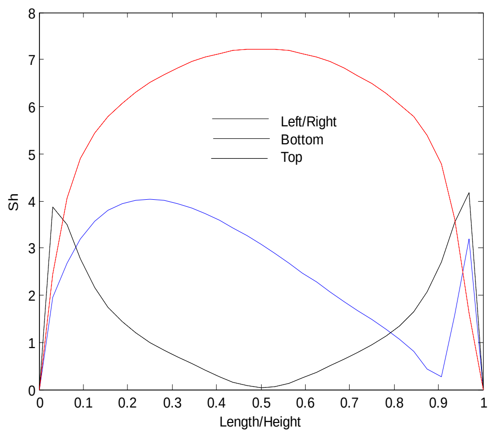

Fig. 16: Local *Sh* at *Ra=100, N=0.2, Le=2, R_d=0.5, Sr=0.5, D=0.25*

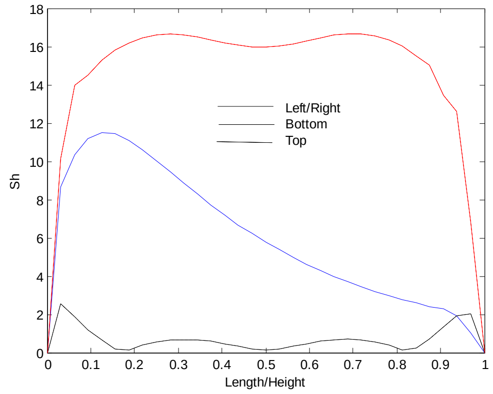

Fig. 17: Local *Sh* at *Ra=100, N=0.2, Le=10, R_d=0.5, Sr=0.5, D=0.25*

Figs. 18 and 19 illustrate the effect of the buoyancy ratio on mass transfer at the outer walls of the annulus. These figures were obtained at Ra=100, Le=1, R_d=1, Sr=0.5, D=0.25. As explained earlier, parameter N indicates the relative importance of concentration and thermal buoyancy. It is interesting to note that the increased buoyancy ratio reduces the Sherwood number significantly at the top wall as can be seen by comparing Figs. 18 and 19. This is because of 4 circulation zones formed at higher buoyancy ratios that lead to deeper penetration of higher concentration lines in the upper section of the cavity (Fig. 3). The higher buoyancy ratio results into bottom wall Sherwood number to vary in sinusoidal form with different amplitudes.

The effect of variation in the Soret parameter is demonstrated by Figs. 20 and 21. The Soret effect is nothing but induction of concentration diffusion caused by a thermal gradient that exists across the domain. Thus, the Soret parameter has a more pronounced effect on mass transfer than does heat transfer. This is vindicated by Figs. 20 and 21 which show that an increase in the Soret parameter leads to increased mass transfer at the bottom wall.

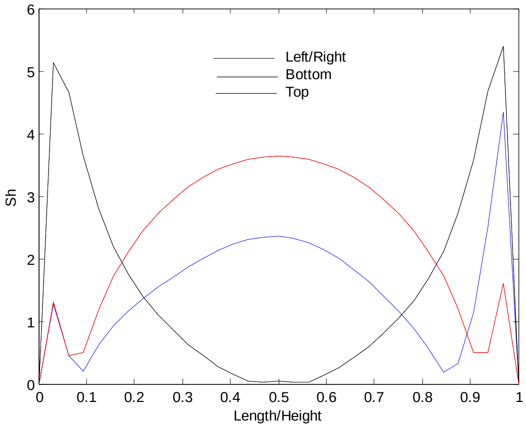

Fig. 18: Local *Sh* at *Ra=100, N=0.5, Le=1, R_d=1, Sr=0.5, D=0.25*

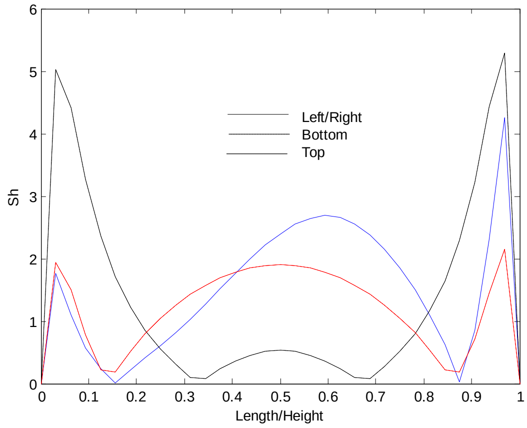

Fig. 19: Local *Sh* at *Ra=100, N=1, Le=1, R_d=1, Sr=0.5, D=0.25*

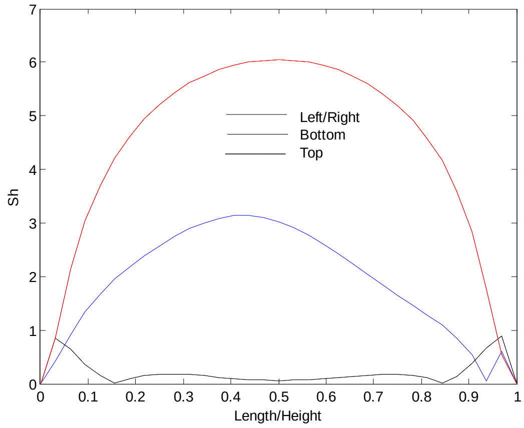

Fig. 20: Local *Sh* at *Ra=100, N=0.5, Le=2, R_d=1, Sr=0.1, D=0.25*

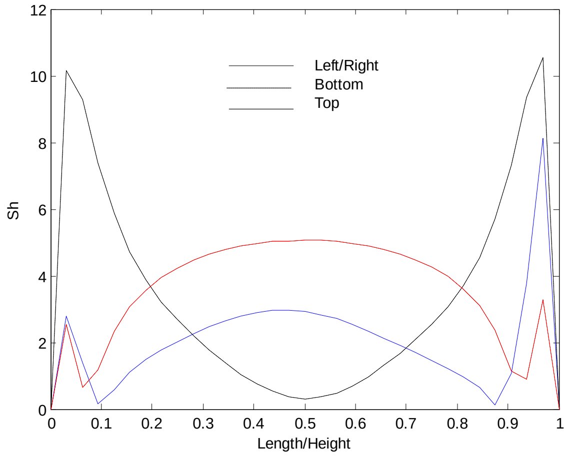

Fig. 21: Local *Sh* at *Ra=100, N=0.5, Le=2, R_d=1, Sr=1, D=0.25*

IV. CONCLUSION

The following conclusions can be drawn from the current study that has investigated the Soret and viscous dissipation effect in a square porous annulus.

- The increase in hollow section of the annulus leads to less temperature variation in the porous medium as compared to that of smaller D
- The mass concentration is higher in the bottom region of the annulus when D is small.
- Increased values of the buoyancy ratio lead to greater concentration gradients across the annulus surfaces.
- In general, the heat transfer at vertical walls is higher than at other walls.
- The Soret parameter has a significant effect on mass transfer when compared to heat transfer.
- The mass transfer at the center of the bottom wall is relative low when compared to other sections of high concentration surfaces.

V. NOMENCLATURE

A Area of element (m^2)
c_p Specific heat of fluid (J/kg-^{o}C)
D Duct hole length (m)
g Acceleration due to gravity (m/s^2)
k Thermal conductivity (W/m-^{o}C)
K Permeability of porous medium (m^2)
L Height of cavity (m)
N_i Shape function
Nu , $\overline{Nu}$ *Local N*usselt number and average Nusselt number respectively
q_r Radiation flux (W/m^2)
R_d Radiation parameter
Ra Modified Raleigh number
T , $\overline{T}$ Dimensional (^{o}C) and non-dimensional Temperature
u, v Velocity components in x and y direction respectively (m/s)
W Width Ratio
Sr Soret Parameter
x, y Cartesian co-ordinates
$\overline{x}$, $\overline{y}$ Non-dimensional co-ordinates

Greek Symbols

α Thermal diffusivity (m^2/s)
β Coefficient of thermal expansion (1/^{o}C)
ρ Density (kg/m^3)
μ, *v* Coefficient of Dynamic (kg/m-s) and kinematic viscosity(m^2/s) respectively
σ Stephan Boltzmann constant (W/m^2-K^4)
β_r Absorption coefficient (1/m)
ψ Stream function
$\overline{\psi}$ Non-dimensional stream function

Subscripts

$_h$ Hot
$_c$ Cold
L Left
R Right
T Top
B Bottom
Tot Total

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