International Journal of Advance Research in Science and Engineering
Volume No.07, Issue No.02, February 2018
www.ijarse.com
IJARSE
ISSN: 2319-8354

IMPACT OF LTNE ON DOUBLE DIFFUSIVE CONVECTION WITH RADIATION IN A SQUARE CAVITY

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ABSTRACT

In this article, we address the influence of heat transfer coefficient on transfer rates in terms of Nusselt numbers (for solid ($\mathrm{N}u_s$) as well as fluid ($\mathrm{N}u_f$)-phase of porous medium) and on mass transfer rate in terms of Sherwood number (Sh) due to thermo-solutal convection in a fluid saturated square (aspect ratio A = 1) porous cavity for buoyancy aiding (N, buoyancy ratio>0) as well as opposed flow (N<0). The left and right walls are maintained at constant temperatures and concentration, while both horizontal walls are adiabatic and impermeable) with local thermal non equilibrium (LTNE) approach. The governing equations (based on Darcy law for isotropic model) and two energy equations (one for each phases: solid and fluid) for local thermal equilibrium (LTNE) model, were solved numerically by finite deference method with ADI scheme.

Keywords : Thermal non-equilibrium model, Natural convection, Darcy model, ADI method.

I.INTRODUCTION

Natural convection due to combined buoyancy effect of thermal and species diffusion can be described as double diffusive convection or thermo-solutal convection (e.g. oceanography [1] and magma chambers [2]). The literature survey for thermo-solutal convection in enclosure has been categorized into two main dimensions: (i) when vertical walls of enclosure were kept at constant heat and mass (e.g., [3, 4]) and (ii) provision of opposing fluxes of heat and mass to the vertical walls (e.g., [5, 6]), while both the horizontal walls are taken as adiabatic and impermeable in both the cases. Also there are many article available in literature in which impact of radiation double diffusive convection has been studied: e.g, [7, 8].

In all above articles researchers have considered local thermal equilibrium (LTE) situations between two phase, in which it was assumed that there is no heat transfer from one phase to other phase but for high speed flow or at sufficiently large Rayleigh number temperatures of solid and fluid phases are no longer identical and state is no more LTE or become LTNE [9, 10]. Hence, two energy equations used to represent for each phase and supplemented with an additional term that models the modes of heat transfer between the two phases. The articles related to the study of natural convection in enclosure using LTNE model is restricted to very few articles: [11, 12].

In the present manuscript impact of radiation on double diffusive convection in pours cavity with radiation is investigated along with LTNE model. According the literature survey we concluded that there is no article is available in with concept of radiation and $LTNE$ with double diffusion in enclosure was not take care by any researchers as per our knowledge. Our work is basically the extension of [12] by incorporating the buoyancy effects due to variations in concentration in same geometry, which subject to the same boundary conditions.

II.MATHEMATICAL FORMULATION

Here, we consider double diffusive natural convection in a square fluid saturated porous cavity, whose left and right wall are maintained at temperature T_1 and T_2 $(T_1 > T_2)$, concentrations C_1 and C_2 $(C_1 > C_2)$, respectively and both horizontal walls are insulated and impermeable, as shown schematically in Fig1. The fluid and porous medium are everywhere in local thermal non-equilibrium i.e. the temperature of fluid and solid phases are defined by different energy equations. Darcy model has been adopted and porous medium is assumed to be homogeneous and hydro dynamically as well as thermally isotropic. The thermal physical properties are constant except for the density dependence of the buoyancy body-force term in momentum equation. The fluid that saturates the porous matrix is modeled as a Boussinesq fluid whose density varies linearly with temperature and concentration as ($\rho = \rho_0[1 - \beta_T(T_1 - T_2) - \beta_C(C_1 - C_2)]$), is valid. The gravitational force is aligned in the negative y -direction. The fluid is transparent to radiation. The medium behaves as an optically thick gray body and the radiative heat flux in the y direction is negligible in comparison to that in the x direction.

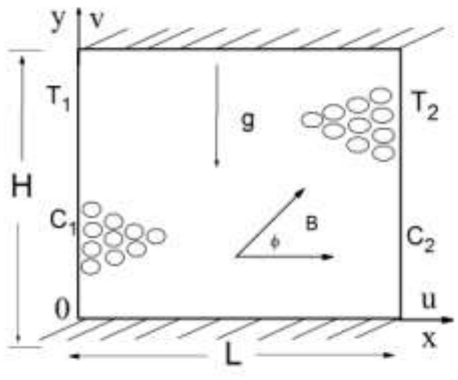

Fig.1. Schematic of Physical Problem.

Dimensional form of governing equations:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial y}-\frac{\partial u}{\partial x}=-\frac{gK\rho_o}{\mu}\left(\beta_T\frac{\partial T_f}{\partial x}-\beta_C\frac{\partial C}{\partial x}\right) \tag{2}$$

$$\varepsilon(\rho c_P)_f\frac{\partial T_f}{\partial t}+(\rho c_P)_f\left(u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}\right)=\varepsilon k_f\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}\right)+h(T_s-T_f) \tag{3}$$

$$(1-\varepsilon)(\rho c_P)_s\frac{\partial T_s}{\partial t}=(1-\varepsilon)k_s\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}\right)+h(T_f-T_s)+(1-\varepsilon)\frac{\partial q_r}{\partial x} \tag{4}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \tag{5}$$

With boundary conditions:

$$v=0,\ T_f=T_s=T_1,\ \text{C=C}_1,\quad \text{at x =0} \tag{6}$$

$$v=0,\ T_f=T_s=T_2,\ \text{C=C}_1,\quad \text{at x =1} \tag{7}$$

$$u=0,\frac{\partial T_f}{\partial y}=\frac{\partial T_s}{\partial y}=\frac{\partial C}{\partial y}=0,\ \text{ at y=0,1.} \tag{8}$$

No-dimensional quantities:

$$x^*=\frac{x}{L},\ y^*=\frac{y}{L},\ t^*=\frac{k_f t}{L^2(\rho c_P)_f},\ (u,v)^*=\frac{(u,v)L(\rho c_P)_f}{\varepsilon k_f},\ \theta_f^*=\frac{(T_f-T_2)}{(T_1-T_2)},\ \theta_s^*=\frac{(T_s-T_2)}{(T_1-T_2)},\ c=\frac{(C-C_2)}{(C-C_1)}$$

along with the non-dimensional stream function: $u=\frac{\partial\psi}{\partial y},\ v=-\frac{\partial\psi}{\partial x}$

Invoking Rosseland approximation for radiation flux as: $q_r=-\frac{4\sigma}{\beta_R}\frac{\partial(T)}{\partial y}$

Expanding T^4 in Taylor series about T_c and neglecting higher order terms: $T^4\approx 4TT_C^3-3T_C^4$, and dropping asterisk, the

Non-dimensional governing equations are:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=-R_T\left(\frac{\partial\theta_f}{\partial x}-N\frac{\partial c}{\partial x}\right) \qquad (9)$$

$$\frac{\partial\theta_f}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial\theta_f}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial\theta_f}{\partial y}=\frac{\partial^2\theta_f}{\partial x^2}+\frac{\partial^2\theta_f}{\partial y^2}+H(\theta_s-\theta_f) \qquad (10)$$

$$\sigma\frac{\partial\theta_s}{\partial t}+\frac{\partial^2\theta_s}{\partial x^2}+\frac{\partial^2\theta_s}{\partial y^2}=-\gamma H(\theta_f-\theta_s)-\frac{4R_d}{3}\frac{\partial^2\theta_s}{\partial x^2} \qquad (11)$$

$$\frac{\partial c}{\partial t}+\frac{\partial\psi}{\partial y}\frac{\partial c}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial c}{\partial y}=\frac{1}{Le}\left(\frac{\partial^2 c}{\partial x^2}+\frac{\partial^2 c}{\partial y^2}\right) \qquad (12)$$

The non-dimensional boundary conditions over the walls of enclosure are:

$$\theta_f=\theta_s=c=0.5,\ \psi=0,\ \text{at } x=0 \qquad (13)$$

$$\theta_f=\theta_s=c=-0.5,\ \psi=0,\ \text{at } x=1 \qquad (14)$$

$$\frac{\partial\theta_f}{\partial y}=\frac{\partial\theta_s}{\partial y}=\frac{\partial c}{\partial y}=\psi=0,\ \text{at y}=0,1. \qquad (15)$$

Heat and Mas Transfer rates:

The corresponding over all heat transfer rates in terms of Nusselt number, for fluid ($\mathrm{N}u_f$) as well as solid ($\mathrm{N}u_s$) and mass transfer rate in terms of Sherwood number (Sh) are given by as follows:

$$\mathrm{N}u_f=\left(1+\frac{4R_d}{3}\right)\int_0^1\left[-\frac{\partial\theta_f}{\partial x}\right]_{x=0,1}dy, \qquad \mathrm{N}u_s=\int_0^1\left[-\frac{\partial\theta_s}{\partial x}\right]_{x=0,1}dy, \qquad Sh=\int_0^1\left[-\frac{\partial c}{\partial x}\right]_{x=0,1}dy$$

Nomenclature:

In the all above equations, u,v,T_f and T_s are the velocity components along x-axis, velocity component along y axis, temperature of fluid phase and temperature for solid phase, respectively. Apart from these, $D,\rho,g,K,\varepsilon,t,C,\beta_{T,}\beta_C,c_P,\upsilon,k_f,k_s,q_r$ and h denote mass diffusivity of species, density of the fluid, acceleration due to gravity, permeability of the porous medium, porosity, time, concentration, the volumetric thermal expansion, solutal expansion coefficient, specific heat at a constant pressure, kinematic viscosity, thermal conductivity of fluid, thermal conductivity of solid, radiative flux in y-direction and volumetric heat transfer coefficient, respectively. Apart from these in non-dimentional equations, A, R_T, R_d, H, Le, N and γ are aspect ratio, Rayleigh-Darcy number, Radiation parameter, interface heat transfer coefficient, Lewis number, buoyancy ratio and porosity scaled thermal conductivity ratio, respectively.

III.NUMERICAL SOLUTION AND ITS VALIDATION

3.1Procedure

Here, we adopt finite difference method (temporal and spacial derivatives are approximated by first and second order discretizations, respectively.) along with ADI scheme to solve non-linear partial differential equations $(9)-(12)$, along with hydrodynamic thermal and solutal boundary conditions $(13)-(15)$, in which time dependent governing equations are marched in time until a steady state solution is obtained. Stream function is calculated by via a successive over relaxation method (SOR) with relaxation factor 1.3. The solution procedure is iterated until the following convergence criterion is satisfied:

$$\sum_{i,j} | x_{i,j}^{new} - x_{i,j}^{old} | /(nm) \leq 10^{-6}$$

Where, n, m are number of grid points along x and y direction, respectively. In entire calculation uniform mesh sizes have been considered for x and y directions.

3.2Validation

In order to prove the accuracy of our result and to show strong validation we adopted two ways:

(i) ***Grid independency test***: Table. 1 shows that, 181×181 is sufficient to describe the flow dynamics inside a cavity.

(ii) **Comparison with Published results**: We compare our result with published result [12]. Table 2. shows that the computed heat transfer rate for fluid as well for solid found to be in the excellent agreement with in [12] for pure thermal diffusive case (i.e. , $N = 0$).

Table 1. : Grid independency for $A, R_T = 100, R_d = 0, H = 10, Le = 1, N = 0, \gamma = 10$		**H**	**Table 2. Comparison of our result with published article [12]**			
Grid Points	θ_f		**Published Result [12]**		**Present Result**	
101x101	3.3678627	10	14.14	1.476	14.14	1.476
121x121	3.3542280	100	13.10	3.182	13.10	3.182
151x151	3.3335560	500	12.24	5.108	12.24	5.108
201x201	3.3355296	1000	11.79	5.984	11.79	5.984

IV.RESULTS AND DISCUSSIONS

Results in this section illustrate the effect of local thermal non-equilibrium (LTNE) parameters on double diffusive convection with radiation in a cavity. To understand the impact of LTNE state on double-diffusive convection in the enclosure, we have split this section into two subsections. In the first one both buoyancy forces (thermal as well as solutal) are in favor of each other (i.e., N> 0), which is known as buoyancy aiding flow. In the second one, buoyancy forces are against of each other (i.e., N< 0), which is known as buoyancy opposed flow. The first one is governed by considering N as positive whereas second on by considering N as negative. There are six non-dimensional parameters, in which four for LTE model namely: Rayleigh-Darcy number (R_T), Radiation parameter (R_d), buoyancy ratio (N) and Lewis numbers (Le) and two parameters due to consideration of approach LTNE approach, namely: inter-phase heat transfer coefficient (H) and the

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thermal conductivity ratio (γ). In the actual computations R_T is fixed at 100 in entire calculation.

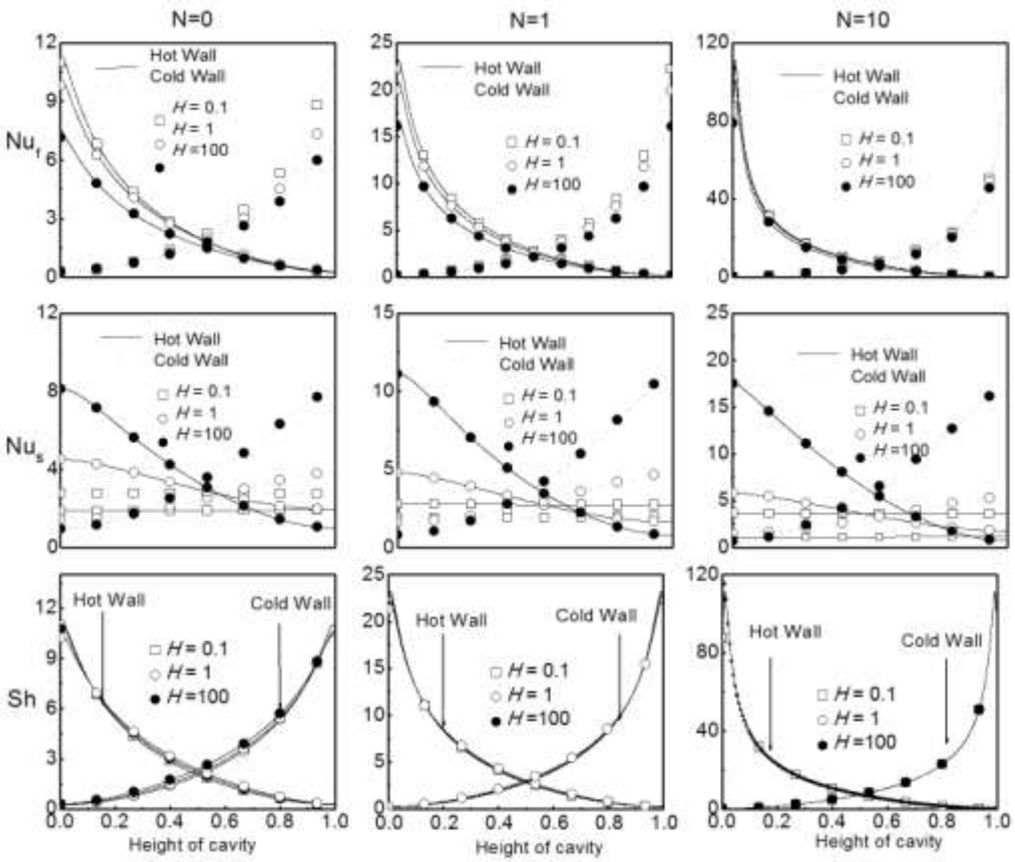

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Fig. 2. Variation of Nusselt and Sherwood Number as a function of height for Le=γ = R_d=1.

4.1BUOYANCY AIDING FLOW

In this subsection influence of LTNE parameters, in the name of H and γ, on local heat and mass transfer rates has been investigated for buoyancy aiding flow see Fig 2. For this three positive values (0, 1, 10) of buoyancy ratio of N have been taken, , while the values of R_d , γ and Le are fixed at1. From Fig. 2 following observations have been observed. First, in case of buoyancy aiding flow, for all values of H as well as N, heat transfer rates (for fluid as well as solid) and mass transfer rate decreases on increasing height of hot wall of cavity, whereas they all shows reverse behaviors along the cold wall of the cavity. Second, enhancement of H enhances heat transfer rates solid phase along both the walls, while enhancement of same parameters reduces heat transfer rates for fluid. Third, variation in Sherwood number is negligible with respect to H. Finally, enhancement of buoyancy ration increases both heat as well as mass transfer rates which are very large magnitude wise.

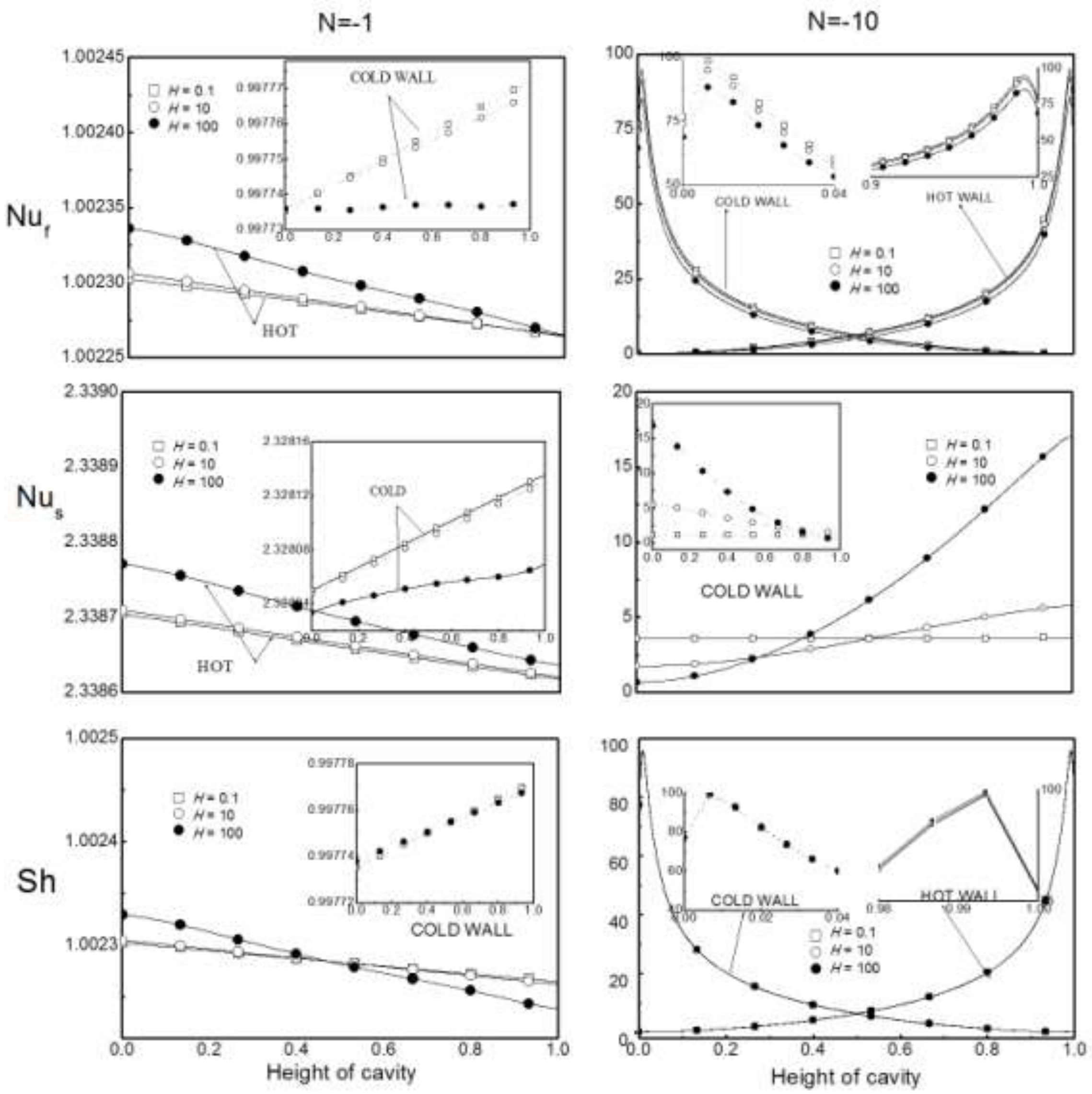

Fig. 3. Variation of Nusselt and Sherwood Number for buoyancy oopcsed flow.

4.2BUOYANCY OPPOSED FLOW

This subsection deals with the study of double diffusive convection with radiation using LTNE model for buoyancy opposed flow (i.e. N<0). To fulfill our desire we just plot Fig. 3. For this two different negative values (-1, -10) of N and three different values (0.1, 0, 00) of interphase heat transfer coefficient (H) have been chosen, while value of other parameter except R_T have been fixed at 1. Fig. 3 discloses following facts: (i) Enhancement of height of enclosure along hot wall reduces heat transfer rates (for both phases) as well as mass transfer rates for all values of N as well as H, while behavior of heat and mass transfer rates is reverse with respect to cold wall, (ii) same as buoyancy aiding flow here also increment in H increases heat transfer rate for solid and decreases heat transfer rate for fluid phases of porous medium, while mass transfer rate is independent on interphase heat transfer cooficient.

V.CONCLUSIONS

We have taken an attempt to understand the influence LTNE parameter on double diffusive natural convection in fluid saturated porous cavity, in which flow is induced by imposing constant temperatures (for fluid as well as solid phases) as well as constant concentration at the vertical walls, when horizontal walls are in adiabatic state. To define the flow, we have adopted Darcy model. With the help of numerical experiments, we are able to extract detailed about the behavior of heat transfer rates for both phases as well as mass transfer rate in for buoyancy aiding as well as opposed flow. As we have clarified earlier that, our main objective for this study is to examine the effect of radiation parameter heat transfer rates (for fluid as well as solid) and mass transfer rate for different values of non-equilibrium parameters (i.e., interphase heat transfer coefficient, H, and conductivity ratio, γ) in a square cavity. Hence we have fixed the value of (R_T) and Aspect ratio (A) as 100 and 1 , respectively, in entire calculations. The following conclusions can be drawn from this study: (i) For all value of interphase heat transfer coefficient enhancement of buoyancy ratio in magnitude enhances heat transfer rates (for fluid, $\mathrm{N}u_f$ as well as solid, $\mathrm{N}u_s$) and mass transfer rate, Sh .(ii) In case of buoyancy aiding flow, increment of height of the hot wall of the cavity decrease Heat as well as mass transfer rates whereas in case of cold walls of the cavity it acts in Otherwise, while for buoyancy opposed flow the behaviors of $\mathrm{N}u_f$, $\mathrm{N}u_s$ and Sh with respect to walls of cavity reverse of buoyancy aiding flow.

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