International Journal of Heat and Mass Transfer 85 (2015) 401–413

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of buoyancy ratio on unsteady double-diffusive natural convection in a cavity filled with porous medium with non-uniform boundary conditions

Sabyasachi Mondal *, Precious Sibanda

School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Scottsville, Pietermaritzburg, South Africa

A R T I C L E   I N F O

Article history:
Received 8 September 2014
Received in revised form 24 January 2015
Accepted 27 January 2015

Keywords:
Double-diffusive convection
Finite-difference method
Non-uniformly heated walls
Non-uniformly concentrated walls
Porous media

A B S T R A C T

The effects of buoyancy ratio on unsteady double-diffusive natural convection in a cavity filled with porous medium with uniform and non-uniform boundary conditions are analyzed in this paper. It is assumed that the left vertical wall and bottom wall are heated and concentrated (uniformly and non-uniformly), while the right vertical wall is maintained at a constant cold temperature, and the top wall is well insulated. The governing equations are solved numerically using a staggered grid finite-difference method to determine the streamlines, isotherms, isoconcentrations, local Nusselt number, local Sherwood number, average Nusselt number and average Sherwood number for various values of buoyancy ratio and Rayleigh number. The change of flow patterns with respect to time depicted and described here. The results are compared with previously published work and excellent agreement has been obtained.

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1. Introduction

Studies of flow through porous medium have attracted considerable research attention in recent years because of their several important applications notably in the flow through packed beds, extraction of energy from geothermal regions, filtration of solids from liquids, flow of liquids through ion-exchange beds, the evaluation of the capability of heat removal from nuclear fuel debris that may result from an accident in a nuclear reactor and in chemical reactors for the separation or purification of mixtures [1–4].

Fluid flow, heat and mass transfer induced by double-diffusive natural convection in fluid saturated porous media have practical importance in many engineering applications [5]. This aspect of fluid dynamics has gained considerable attention in recent years among researchers. The migration of moisture in fibrous insulation, drying processes, chemical reactors, transport of contaminants in saturated soils and electro-chemical processes are some examples of double-diffusive natural convection phenomena. Double-diffusion occurs in a wide range of scientific fields such as oceanography, astrophysics, geology, biology and chemical processes. In the recent past, a significant number of researchers have shown a keen interest in the study of heat and mass transfer in enclosures and cavities. Double-diffusive natural convection in cavities has been subject to an intensive research due to its importance in engineering and geophysical problems. This includes nuclear reactors, solar ponds, geothermal reservoirs, solar collectors, crystal growth, electronic cooling and chemical processing equipments.

The numerical investigation of natural convection in porous trapezoidal enclosures has been performed for uniformly or non-uniformly heated bottom wall by Basak et al. [6]. Sathiyamoorthy et al. [7] studied non-Darcy buoyancy flow in a square cavity filled with porous medium for various temperature difference aspect ratios. Deng et al. [8] investigated fluid, heat and contaminant transport structures of laminar double diffusive mixed convection in a two-dimensional ventilated enclosure numerically. Roy et al. [9] performed finite element simulation on natural convection flow in a triangular enclosure due to uniform and non-uniform bottom heating. Later, Alimi et al. [10] studied the buoyancy effects on mixed convection heat and mass transfer in an inclined duct preceded with a double step expansion. Brown and Lai [11] numerically examined combined heat and mass transfer from a horizontal channel with an open cavity heated from below numerically. Teamah [12] studied double-diffusive convective flow in a rectangular enclosure with the upper and lower surfaces being insulated and impermeable by imposing constant temperature and concentration along the left and right walls of the enclosure and a uniform magnetic field was applied in a horizontal direction. Saha et al.

* Corresponding author.
E-mail addresses: sabya.mondal.2007@gmail.com (S. Mondal), sibandap@ukzn.ac.za (P. Sibanda).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.129
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[13] investigated the new characteristics of the airflow and heat/contaminant transport mechanism inside a vented cavity in terms of streamlines, isotherms and isoconcentration lines.

Minkowycz et al. [14] showed that the discontinuity can be avoided by choosing a non-uniform temperature distribution along the walls (i.e. non-uniformly heated walls). Roy and Basak [15] solved the nonlinear coupled partial differential equations for flow and temperature fields with both uniform and non-uniform temperature distributions prescribed at the bottom wall and at one vertical wall. Teamah et al. [16] studied the effect of the heater length, Rayleigh number, Prandtl number and buoyancy ratio on both average Nusselt and Sherwood number with uniform heating at left vertical wall. Karimi-Fard et al. [17] studied double diffusive natural convection in a cavity filled with a porous medium. Patil et al. [18] investigated double diffusive mixed convection flow over a vertical plate. Nithiarasu et al. [19] studied the development of the variable porosity model in natural convection heat transfer in detail. Recently, Mahapatra et al. [20] investigated the effects of buoyancy ratio and the thermal Rayleigh number on double diffusive natural convection in a cavity when the boundaries are uniformly and non-uniformly heated and concentrated.

The aim of this investigation is to study the effects of buoyancy ratio and Rayleigh number on the heated and concentrated walls in terms of streamlines, isotherms, isoconcentrations, local Nusselt number, average Nusselt number, local Sherwood number and average Sherwood number when the bottom wall and left vertical wall are heated and concentrated (uniformly and non-uniformly), right vertical wall is cooled by means of a constant temperature and top wall is well insulated. The thermal and mass exchanges generated in the case of co-operating thermal and concentration buoyancy effects with uniform and non-uniform boundary conditions have been analyzed.

2. Governing equations and boundary conditions

An unsteady-state two-dimensional square cavity of height L as shown in Fig. 1 is considered. It is assumed that the top wall is considered to be adiabatic. The bottom wall and left vertical wall are heated and concentrated (uniformly and non-uniformly) and right vertical wall is cooled by means of a constant temperature. The thermophysical properties of the fluid are assumed to be constant except the density variation in the buoyancy force, which is approximated according to the Boussinesq approximation. This variation, due to both temperature and concentration gradients, can be described by the following equation:

$$\rho = \rho_0[1 - \beta_T(T - T_c) - \beta_S(C - C_c)] \tag{1}$$

where β_T and β_S are the thermal and concentration expansion coefficients, respectively. In the cartesian coordinate system, the fundamental governing equations are as follows (see Marcondes et al. [21], Mahapatra et al. [22] and Mahapatra et al. [23]):

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0, \tag{2}$$

$$\frac{\partial U}{\partial t'} + \frac{U}{\epsilon}\frac{\partial U}{\partial X} + \frac{V}{\epsilon}\frac{\partial U}{\partial Y} = -\frac{1}{\rho}\frac{\partial P}{\partial X} + \nu\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \frac{\nu\epsilon}{K}U - \frac{1.75\sqrt{U^2+V^2}}{\sqrt{150K\epsilon}}U, \tag{3}$$

$$\frac{\partial V}{\partial t'} + \frac{U}{\epsilon}\frac{\partial V}{\partial X} + \frac{V}{\epsilon}\frac{\partial V}{\partial Y} = -\frac{1}{\rho}\frac{\partial P}{\partial Y} + \nu\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) - \frac{\nu\epsilon}{K}V - \frac{1.75\sqrt{U^2+V^2}}{\sqrt{150K\epsilon}}V + g\beta(T - T_c) + g\beta_S(C - C_c), \tag{4}$$

$$\frac{\partial T}{\partial t'} + U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \alpha\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right), \tag{5}$$

$$\frac{\partial C}{\partial t'} + U\frac{\partial C}{\partial X} + V\frac{\partial C}{\partial Y} = D\left(\frac{\partial^2 C}{\partial X^2} + \frac{\partial^2 C}{\partial Y^2}\right). \tag{6}$$

The associated boundary conditions are when $t' = 0$ for $0 \leqslant X, Y \leqslant L$:

$$U(X,Y) = 0 = V(X,Y), \tag{7}$$

$$T(X,Y) = T_c, \quad C(X,Y) = C_c, \tag{8}$$

when $t' > 0$ for $0 \leqslant X, Y \leqslant L$:

$$U(X,L) = U(X,0) = U(0,Y) = U(L,Y) = 0, \tag{9}$$

$$V(X,0) = V(X,L) = V(0,Y) = V(L,Y) = 0, \tag{10}$$

$$T(X,0) = T_h \ \text{ or } \ T(X,0) = (T_h - T_c)\sin(\pi X/L) + T_c, \ \ \frac{\partial T}{\partial Y}(X,L) = 0, \tag{11}$$

$$T(0,Y) = T_h \ \text{ or } \ T(0,Y) = (T_h - T_c)\sin(\pi Y/L) + T_c, \ \ T(L,Y) = T_c, \tag{12}$$

$$C(X,0) = C_h \ \text{ or } \ C(X,0) = (C_h - C_c)\sin(\pi X/L) + C_c, \ \ \frac{\partial C}{\partial Y}(X,L) = 0, \tag{13}$$

$$C(0,Y) = C_h \ \text{ or } \ C(0,Y) = (C_h - C_c)\sin(\pi Y/L) + C_c, \ \ C(L,Y) = C_c. \tag{14}$$

where, X and Y are the distances measured along the horizontal and vertical directions respectively; U and V are velocity components in the X- and Y- directions respectively; T and C denote the temperature and concentration respectively; ν, α and D are kinematic viscosity, thermal diffusivity and mass diffusivity respectively; P is the pressure and ρ is the density; T_h and T_c are the temperatures at the hot and cold walls respectively; C_h and C_c are the concentrations at the hot and cold walls respectively; L is the side of the square cavity. We now introduce dimensionless variables given as follows:

$$t = \frac{\alpha t'}{L^2}, \quad x = \frac{X}{L}, \quad y = \frac{Y}{L}, \quad u = \frac{UL}{\alpha}, \quad v = \frac{VL}{\alpha}, \quad p = \frac{PL^2}{\rho\alpha^2}, \tag{15}$$

$$\theta = \frac{T - T_c}{T_h - T_c}, \quad S = \frac{C - C_c}{C_h - C_c}. \tag{16}$$

Here x and y are dimensionless coordinates along the horizontal and vertical directions respectively; u and v are dimensionless velocity components in the x- and y- directions respectively; θ and S denote the dimensionless temperature and concentration respectively; p is the dimensionless pressure parameter.

Using these dimensionless variables, we obtain the following dimensionless governing equations from the Eqs. (2)–(6):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{17}$$

$$\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + Pr\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{1}{\epsilon}\left(\frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y}\right) - \frac{Pr\epsilon}{Da}u - \frac{1.75\sqrt{u^2+v^2}}{\sqrt{150Da\epsilon}}u, \tag{18}$$

$$\frac{\partial v}{\partial t} = -\frac{\partial p}{\partial y} + Pr\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{1}{\epsilon}\left(\frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x}\right) - \frac{Pr\epsilon}{Da}v - \frac{1.75\sqrt{u^2+v^2}}{\sqrt{150Da\epsilon}}v + PrRa(\theta + NS), \tag{19}$$

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