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Effects of buoyancy ratio on double-diffusive natural convection in a lid-driven cavity

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ABSTRACT

The effects of uniform and non-uniform heating of wall(s) on double-diffusive natural convection in a lid-driven square enclosure are analyzed. It is assumed that the left vertical wall and bottom wall are heated and concentrated (uniformly or non-uniformly), while the other vertical wall is maintained at a constant cold temperature and the top wall is well insulated which moves with a constant speed. The governing equations are solved numerically using staggered grid finite-difference method. Streamlines, isotherms, local Nusselt number, local Sherwood number, average Nusselt number and average Sherwood number for various values of buoyancy ratio and thermal Rayleigh number are obtained. The results are compared with previously published work and excellent agreement has been obtained.

1. Introduction

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

Wee et al. [1] and Beghein et al. [2] presented comprehensive reviews on the study of heat and moisture transfer by natural convection in a rectangular cavity. Thereafter, Ghorayeb et al. [3] analyzed the onset of oscillatory flow in double diffusive convection in a square cavity with equal but opposing horizontal temperature and concentration gradients numerically. The results presented the influence of the Lewis number on the transition of steady state convective and oscillatory flow structures occurring beyond this transition. Deng et al. [4] investigated fluid, heat and contaminant transport structures of laminar double diffusive mixed convection in a two-dimensional ventilated enclosure numerically. The effect of thermal modulation on the onset of double-diffusion natural convection in a horizontal fluid layer was studied analytically and numerically using a linear stability analysis by Malashetty et al. [5]. They found that the frequency symmetric modulation was destabilizing while high frequency symmetric modulation was always stabilizing.

The effects of combined thermal and solutal buoyancy induced by temperature and concentration gradients have, however, not been widely studied. Yan [6,7] and Lee et al. [8] analyzed the transport phenomena of developing laminar mixed convection heat and mass transfer in rectangular ducts. Later, Alimi et al. [9] studied the buoyancy effects on mixed convection heat and mass transfer in an inclined duct preceded with a double step expansion. Brown and Lai [10] numerically examined combined heat and mass transfer from a horizontal channel with an open cavity heated from below numerically. Teamah [11] 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. [12] investigated the new characteristics of the airflow and heat/contaminant transport mechanism inside a vented cavity in terms of streamlines, isotherms and isoconcentration lines.

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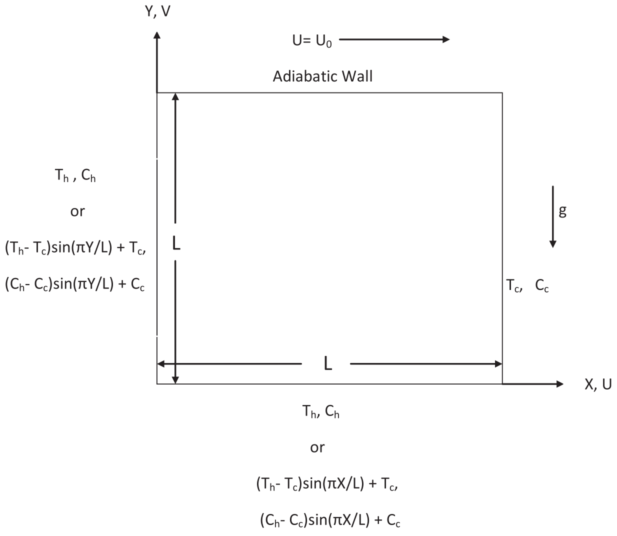

Fig. 1. Schematic diagram of the physical system.

Kuznetsov and Nield [13] studied the double-diffusive natural convective boundary-layer flow of a nanofluid past a vertical plate analytically. Later, Nield and Kuznetsov [14] presented an analytical treatment of double-diffusive nanofluid convection in a porous medium. Teamah et al. [15] studied the effects for a wide range of thermal Grashof number and aspect ratio coupled with the inclination angle. The obtained results for average Nusselt and Sherwood numbers were correlated. Trevisan and Bejan [16] investigated the phenomenon of natural convection caused by combined temperature and concentration buoyancy effects in a rectangular enclosure with uniform heat and mass fluxes applied along the vertical walls numerically and analytically. They found that in the case of uniformly heated walls, the finite discontinuity in the temperature distribution appeared at the right edge of the bottom wall. Minkowycz et al. [17] discovered that the discontinuity can be avoided by choosing a non-uniform temperature distribution along the walls (i.e. non-uniformly heated walls), in an investigation on mixed convection flow over a vertical plate, which is non-uniformly heated/cooled. Roy and Basak [18] 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. [19] 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.

Heat and mass transfer in lid-driven enclosures have received less attention in the above literature. In drying technology, better understanding of the drying process is vital for optimum performance of the drying chamber. Alleborn et al. [20] investigated a two-dimensional flow accompanied by heat and mass transport in a shallow lid-driven cavity with a moving heated lid and a moving cooled lid. Their results showed that the drying rates were enhanced by increasing the velocity and become increasingly independent of the gravity orientation because of the dominance of forced convection. Wan and Kuznetsov [21] investigated the

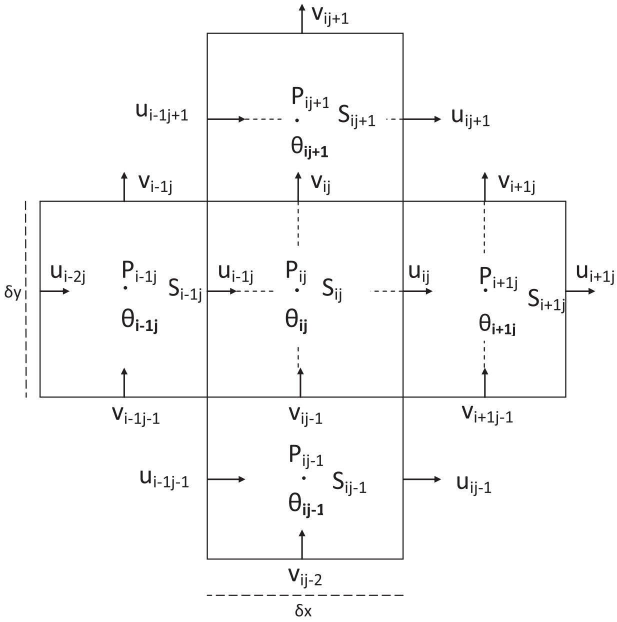

Fig. 2. Control volume for u-momentum, v-momentum, temperature and concentration equations.

Table 1
Grid independence test when $P_r = 0.7$, $Le = 2.0$, $N = 1$, $A = 1$ and $Ra^* = 10^3$.

No. of Grid points	Uniformly heated and uniformly concentrated		Non-uniformly heated and non-uniformly concentrated	
	Iteration	$\lvert\psi_{min}\rvert$	Iteration	$\lvert\psi_{min}\rvert$
20 × 20	19,493	2.1149	19,856	1.8134
40 × 40	78,004	2.0906	79,449	1.7924
80 × 80	312,806	2.0856	318,646	1.7887
160 × 160	1,251,253	2.0846	1,274,605	1.7878

Table 2
Computed values of $\overline{Nu}_H|_{y=0}$ and $\overline{Nu}_H|_{x=0}$ when $P_r = 0.7$, $Le = 2.0$, $A = 1$ and $N = 1.0$ for various values of Ra^*.

Ra^*	N	Uniformly heated and uniformly concentrated		Non-uniformly heated and non-uniformly concentrated	
		$\overline{Nu}_H\|_{y=0}$	$\overline{Nu}_H\|_{x=0}$	$\overline{Nu}_H\|_{y=0}$	$\overline{Nu}_H\|_{x=0}$
10^3	1.0	4.293	0.409	1.325	0.186
10^4		5.424	0.779	2.263	0.391
2×10^4		5.891	0.980	2.659	0.524
5×10^4		6.663	1.318	3.299	0.739
10^5		7.421	1.663	3.863	0.969
2×10^5		8.351	2.120	4.555	1.269
5×10^5		9.859	2.918	5.670	1.765
8×10^5		10.783	3.416	6.340	2.063
10^6		11.265	3.676	6.684	2.217

Table 3
Computed values of $\overline{Sh}_H|_{y=0}$ and $\overline{Sh}_H|_{x=0}$ when $P_r = 0.7$, $Le = 2.0$, $A = 1$ and $N = 1.0$ for various values of Ra^*.

Ra^*	N	Uniformly heated and uniformly concentrated		Non-uniformly heated and non-uniformly concentrated	
		$\overline{Sh}_H\|_{y=0}$	$\overline{Sh}_H\|_{x=0}$	$\overline{Sh}_H\|_{y=0}$	$\overline{Sh}_H\|_{x=0}$
10^3	1.0	4.671	0.515	1.613	0.204
10^4		6.162	1.176	2.849	0.672
2×10^4		6.790	1.468	3.377	0.861
5×10^4		7.813	1.993	4.221	1.176
10^5		8.799	2.529	4.963	1.512
2×10^5		10.010	3.20	5.845	1.929
5×10^5		11.947	4.349	7.251	2.601
8×10^5		13.13	5.075	8.087	3.019
10^6		13.75	5.459	8.514	3.245