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Buoyancy driven double diffusive moisture convection inside the fluid-porous-solid sandwiched building enclosure containing internal heating sources

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ABSTRACT

Double diffusive convection in an enclosure partially inserted with heat-generated porous layer and solid layer is investigated numerically. Moist air motions are simultaneously driven by the internal heat generation and external concentration difference imposed across the enclosure. Identical porous and solid layers are attached to the vertical walls, and the walls are held at constant temperatures and concentrations. The horizontal walls of the enclosure are assumed to be adiabatic and impermeable. The aspect ratio of the cavity is equal to 1.0 and the saturating fluid is moist air ($Pr = 0.7$ and $Le = 0.8$). Present research covers the range of Ra_t from 10^3 to 10^7, N from -10.0 to 10.0, Da from 10^{-9} to 10^{-1}, Φ from $-90°$ to $90°$, and Kr_f and Kr_s from 0.1 to 10.0. The results show that the thermal and solutal buoyancy forces are always aiding with each other and the minus sign of N only has influence on the fluid orientations. For the vertical case, heat and moisture transfer of fluid/porous interface is analyzed as a function of the buoyancy ratio. Average Nusselt and Sherwood numbers are increasing functions of Ra_t, N, Kr_p and Kr_s. Furthermore, volume averaged heat transfer rate as functions of inclination angle, for $N > 0.0$, is presented like a sinusoid, where the maximum is near at $\Phi = 45°$ and 135°, whereas the minimum is located at $\Phi = 90°$. Present research could benefit future development of sustainable building energy storage.

1. Introduction

With the rapid depletion of the fossil fuels and the increase of global energy demand, solar energy has been considered as an effective alternative by many researchers as the earth surface receives abundant solar energy throughout the whole calendar year. The thermal storage wall has been used more extensively in buildings to store the solar energy [1]. In general, thermal energy storage system consists of porous materials, such as alumina and zeolite that are used for dehumidification and removal of pollutant gases from air [2,3]. However, thermal storage wall has the drawback of low thermal resistance, which leads to heat loss at night. Furthermore, as the energy storage and supply cannot be controlled, there is a possibility of overheating in the heated room. A composite-wall, which consists of porous and solid layers, may overcome this drawback.

Many works in this topic concern thermal natural convection in enclosures containing simultaneously a fluid reservoir and a porous layer saturated with the same fluid. Singh et al. [4] investigated a composite cavity containing a fluid layer overlying a porous layer saturated with the same fluid. The amount of fluid penetration into the porous layer depends strongly upon the Darcy, thermal and solutal Rayleigh numbers and heat and mass transfer on the heated wall neat the interface depends strongly on the Darcy number. Mharzi et al. [5] made a numerical study of natural thermosolutal convection in an elongated enclosure, partitioned by a vertical porous layer, which observed that the heat and mass transfer were sensitive to the thermal conductivity ratio and solutal diffusivity ratio. Zhao et al. [6] carried out linear stability analysis to predict the onset of double-diffusive convection in superposed fluid and porous layer using a one-equation model. Results illuminated differences in the critical conditions and the flow streamlines at onset compared with the same problems by Chen et al. [7] using a

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Nomenclature

AR	enclosure aspect ratio
d	thickness of porous and solid layers
D	mass diffusivity
Da	Darcy number
g	gravitational acceleration
H	width of the enclosure
k	thermal conductivity
K	permeability of porous medium
Kr	thermal conductivity ratio
Kc	mass diffusion coefficient ratio
L	length of the enclosure
Le	Lewis number
N	buoyancy ratio
Nu	average Nusselt number
P	dimensionless pressure
Pr	Prandtl number
q''	strength of internal heat generation
Ra_T	thermal Rayleigh number
Sh	average Sherwood number
s	concentration of species
S	dimensionless concentration
ΔS	dimensionless concentration difference
t	temperature
T	dimensionless temperature
ΔT	dimensionless temperature difference
u, v	velocity components in x, y direction
U, V	dimensionless velocity components
x, y	Cartesian coordinates
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity
β_t	coefficient of thermal expansion
β_c	coefficient of solutal expansion
ε	porosity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
Φ	angle of the inclination

Subscripts

0	reference state
c	low level
f	fluid
h	higher level
p	porous
s	solid

two-equation model. The influence of isotropic or anisotropic porous layers for natural convection driven by thermal and solutal buoyancy forces in an enclosure has numerically analyzed by Bennacer et al. [8]. They obtained an optimum value of Nusselt number, which was a function of the anisotropic parameter. Gobin et al. [9,10] dealt with the similar problem, where the coupling of the flow penetration in the porous layer with combined buoyancy forces induces a specific behavior of the flow structure and average heat transfer in the enclosure. Baytas et al. [11] investigated the double diffusive natural convection between a saturated porous layer and an overlying fluid layer. The results show that the height of the step at the interface between fluid and porous layer has a significant effect on the flow field and heat and mass transfer from the left-hand to the right-hand walls. The conjugate double-diffusive natural convective flows in a variable porosity layer sandwiched between two walls has been investigated by Al-Farhany et al. [12], which presented results for a variable porosity medium with different values of the non-dimensional governing parameters. Hadidi et al. [13–15] extended previously published numerical studies on double diffusive convection in partially porous 2D enclosures to three dimensions in cubic enclosures, which discussed the effect of the third direction on the flow, heat and mass transfer in comparison with the simplified (2D) approach. A cavity that has a fluid and superposed porous medium with an adiabatic rotating cylinder was studied by Ismael et al. [16], which showed that Rayleigh number, Darcy number and cylinder size could have profound effects on the local and averaged heat transfer.

In addition, solid partition is also considered by many researchers due to inhibition effect in heat and mass transfer. The study of natural convection with radiation in a rectangular enclosure divided by two partitions was numerically examined by Han et al. [17], whom analyzed the influence of the partition configuration in radiation-affected steady-laminar natural convection. Zhao et al. [18] investigated the comparison of vertical enclosures surrounded by thermal diffusive walls and ones inserted with a solid heat conducting partition. A relative low thermal conductivity partition could enhance the heat transfer rate across the enclosure of moderate volume ratio scale. Sankhavara et al. [19] considered the influence of partition length on natural convection in a partially divided square enclosure, which observed that the Nusselt number could decrease with increasing partition length from 0 to 0.5. The research of heat and moisture transfer by conjugate natural convection in a partial enclosure with a solid wall was considered by Liu et al. [20], their results showed that heat transfer potential, mass transfer potential, and volume flow rate can be promoted or inhibited, depending strongly on the wall materials and size, thermal and moisture Rayleigh numbers. Costa [21] has investigated the effects of thermal boundary conditions and thermal conductivity of the partitions on the conjugate natural convection. His research has demonstrated that some different combinations of the placement and length of the partitions could lead to the same thermal performance of the enclosure, the best option being that corresponding to the shorter partitions, and thus to the lower cost of the material used in the partitions. Harzallah et al. [22] performed a vertical enclosure bounded by finite thickness walls with opposing temperature, concentration gradients on vertical walls, which showed that the fluid conduction dominates for higher fluid-to-solid thermal conductivity ratio. Chamkha et al. [23–26] dealt with the problem of natural convection in porous enclosures bounded with a solid wall, which observed an uncommon behavior of the heat transfer with the wall thickness. Hu et al. [27,28] analytically and numerically studied enclosures containing many solid obstacles. It was founded that the presence of solid obstacles suppresses the intensity of convection.

The literature reviews indicate that most of former researches devoted to single or multi-component fluid, such as single component conjugate heat transfer [29,30], internal heat generation fluid [31–34], power-law fluids [35,36], nanofluids [27,37,38], micropolar fluid [39] or porous media [40–46]. However, it can be observed that little information has been obtained for double diffusive convection inside an enclosure with the thermal storage composite wall. The present work is motivated by a need to understanding the heat and moisture transfer in building structures with the thermal storage composite wall, to provide heating engineers with an effective design tool against heat loss.