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Buoyancy driven heat and species transports inside an energy storage enclosure partially saturated with thermal generating porous layers

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ABSTRACT

Combined thermal and moisture convections in an enclosure partially filled with porous medium are numerically and analytically investigated, aiming to enhance moisture transport in the thermal energy storage unit. Two representative configurations of porous layers were taken into considerations, being placed centrally in the space or attached to the vertical walls. Moist air motions are simultaneously driven by the internal heat generation and external concentration difference imposed across the enclosure. Effects of Darcy number, mass diffusion coefficient, thermal Rayleigh number and buoyancy ratio on the heat and moisture transfer across the enclosure are discussed. Heat and mass transfer of the fluid/porous interface is analyzed as a function of the permeability of the porous layer. In the extreme case of high permeability and solutal-driven flow, a scale analysis is applied to predict the order of magnitudes involved in the boundary layer regime. Also, correlations for the average Nusselt and Sherwood numbers based on discrete numerical results are proposed. There is an agreement between the analytical and numerical results of moisture transfer rate, while a slight difference of heat transfer rate is observed due to different configurations of porous layers were imposed. Present research could benefit future development of sustainable building energy storage.

1. Introduction

Thermal energy storage wall has received considerable attentions due to its fundamental importance in energy saving and renewable energy utilization. Porous materials, such as alumina and zeolite that are used for dehumidification and removal of trace gases from air are good adsorbents in thermal energy storage system. When placed in contact with moist air, thermal energy charging and discharging processes of these materials are possibly affected. These mechanisms, in which fluid flows are generated by combing temperature and concentration buoyancy forces, are called double diffusive convection or two components convection [1,2].

Trevisan and Bejan [3,4] investigated natural convection heat and mass transfer in a porous layer using both analytical and numerical techniques, which analyzed the influence of the defining parameters such as thermal Rayleigh number, buoyancy ratio, Lewis number and geometric aspect ratio on the formation of heat and mass transfer regimes. Mamou et al. [5] made a numerical study of double diffusive natural convection in a fluid-saturated vertical porous enclosure. The effects of buoyancy ratio were founded to be rather significant on the heat and mass transfer, especially for the opposing flows, and comprehensive Nusselt and Sherwood number data were presented as functions of the governing parameters. Kalla et al. [6] and Bahoul et al. [8] conducted an analytical and numerical study of thermosolutal convection within a porous slot, respectively. Results showed that, when the aspect ratio is large enough, the prediction based on a parallel flow approximation were strongly confirmed by numerical simulation and demonstrated the existence of multiple steady-state solutions for a given set of the governing parameters. The problem of double diffusive convective flow inside a rectangular porous enclosure in the presence of the heat generation or absorption effects was considered by Chamkha et al. [7]. The obtained results showed that heat generation or absorption porous medium could put greater influences on the average Nusselt number than that on the average Sherwood number. The double diffusive natural convection in a square porous cavity partially heated from below and subjected to a horizontal concentration gradient was warranted by Bourich et al. [9]. They explored the multiplicity of solutions vanished in the presence of horizontal solutal gradients when

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Nomenclature

AR	enclosure aspect ratio
D	mass diffusivity
Da	Darcy number
g	gravitational acceleration
H	width of the enclosure
k	thermal conductivity
K	permeability of porous medium
Kr	porous-to-fluid thermal conductivity ratio
Kc	porous -to-fluid mass diffusion coefficient ratio
l	thickness of the porous layer
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	thermal Rayleigh number
Sh	average Sherwood number
s	concentration of species
S	dimensionless concentration
$\triangle S$	dimensionless concentration difference
t	temperature
T	dimensionless temperature
$\triangle_t$	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

A	thermal diffusivity
β_t	coefficient of thermal expansion
β_c	coefficient of solutal expansion
δ_t	dimensionless thickness of thermal boundary layer
δ_s	dimensionless thickness of solute boundary layer
ε	porosity
ν	kinematic viscosity
ρ	density
Ψ	dimensionless streamfunction
Ω	dimensionless massfunction

Subscripts

0	reference state
c	low level
f	fluid
h	higher level
i	fluid/porous interface
p	porous

critical conditions were reached. Liu et al. [10] preformed an extensive series of numerical simulations of binary mixture natural convection in rectangular enclosures with localized heating and salting from one side, which provide guidance for locating the heating and salting segment. The research of free heat and mass transfer in a porous enclosure with side vents was conducted by Zhao et al. [11], which mainly examined the influence of vent location and enclosure inclination and suggested practices of enhancing heat and moisture transfer for drying processes. Mondal et al. [12] analyzed the effect of buoyancy ratio on unsteady double diffusive natural convection in a cavity filled with porous medium with uniform and non-uniform boundary conditions, depicting the change of flow patterns with respect to time.

It is noticeable that most of former published researches devoted to a porous enclosure, although the porous media occupy only parts of the enclosure in thermal energy storage system. Particularly, the thickness, position and physical properties of porous portion have a substantial impact on the enclosed fluid flow and heat transfer structures. Singh et al. [13] considered 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. [14] formulated the 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. [15] 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. [16] using a 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. [17]. They obtained an optimum value of Nusselt number, which was a function of the anisotropic parameter. Gobin et al. [18,19] 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. The conjugate double-diffusive natural convective flows in a variable porosity layer sandwiched between two walls has been investigated by Al-Farhany et al. [20], which presented that the wall thickness and thermal conductivity ratio have significant influence on the Nusselt and Sherwood numbers. N. Hadidi et al. [21,22] focused on the double-diffusive convection generated in a bi-layered porous cavity, where a scale analysis was used to predict the heat and mass transfer rates.

Aforementioned studies mainly concentrated on the heat and mass transfer inside an enclosure partially filled with porous medium. Nevertheless, moisture plays a key role on thermosolutal convection occurring in building thermal energy charging and discharging processes. This research is motivated by a need to understanding the moisture behavior of thermal energy storage walls in building structures, to provide heating engineers with an effective design tool against possible moisture problems, as past publications [23–28] are inadequate for considering this problem.

In this paper, the major features of steady-state double diffusive natural convection inside two square enclosures, inserted with one or two porous walls with spatially uniform internal heat generation, are to be explored. Following that, detailed parametric investigations will be conducted, regarding of different governing parameters. For some relevant situations, the flow, temperature and concentration fields are also presented and analyzed by the streamlines, isotherms, iso-concentrations and masslines. Finally, conclusions will be drawn for benefiting future thermal storage walls design and relevant fields.

2. Problem statements and mathematical formulations

The physical domain under investigation is sketched in Fig. 1, where two enclosures of height H and width L are filled with a fluid containing a moisture concentration whose mass transfer occurs is under the influence of the gravity field. It is assumed that the dimension in the **z** direction is large enough and the end effects on the flow are negligible,