Applied Thermal Engineering 30 (2010) 977–990

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Combined heat and moisture convective transport in a partial enclosure with multiple free ports

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ARTICLE INFO

Article history:
Received 10 August 2009
Accepted 6 January 2010
Available online 11 January 2010

Keywords:
Enclosure flow
Natural convection
Heatlines
Masslines

ABSTRACT

Combined heat and moisture transport in an enclosure with free ports has been investigated numerically. Enclosed moist air interacts with the surrounding air through these free-vented ports. The governing conservation equations were solved numerically using a control volume-based finite difference technique. Appropriate velocity boundary conditions at each ports are imposed to achieve overall mass conservation across this system. Air, heat and moisture transport structures are visualized respectively by streamlines, heatlines and masslines. Effects of buoyancy ratio, thermal Rayleigh number on convective heat/moisture transfer rate and flow rate across each free-vented port are discussed. Particularly, Numerical results demonstrate that the convective heat and moisture transport patterns and transport rates on horizontal ports greatly depend on properties of porous medium, while the air exchange rate on vertical port is almost unaffected by the buoyancy ratios for most situations.

1. Introduction

Natural convection in porous medium has been studied extensively in past decades, due to it is frequently encountered in chemical transport in packed-bed reactors, melting and solidification of binary alloys, grain storage, food processing and storage, contaminant transport in ground water, crystal growth, the migration of moisture through air contained in fibrous insulation, and etc [1].

In past studies, single component natural convection (thermal convection) in porous enclosures has been paid broadly attentions [1–4]; whereas, multiple component natural convection, particularly the combined heat and moisture transfer in porous enclosures, has received relatively few attentions. Typically, Chamkha and his coauthors numerically investigated the double diffusive buoyancy driven convection in an enclosure filling with porous medium. The effects of cavity inclination, internal heat generation or absorption, thermal and solute buoyancy forces, and Darcy number on the flow field and heat transfer potential were studied in details, which models the heat and moisture convection in a grain storage [5,6]. Kumar and his coauthors performed numerical study of coupled heat and mass transfer in porous enclosures with wavy geometries and thermally stratified boundary conditions, effects of stratification and wavy function on aiding and opposing flows were particularly analyzed [7,8]. Costa numerically investigated double diffusive natural convection in a parallelogrammic porous enclosure filled with moist air, the heat and mass transfer characteristics of parallelogrammic porous enclosure are analyzed on the thermal Rayleigh number, aspect ratio, and inclination angle, both for the situations of combined and opposite heat and moisture flows through the enclosure [9]. Zhao et al. numerically investigated the double diffusive natural convection in a porous enclosure with the simultaneous presence of discrete heat and moisture sources, effects of permeability of porous medium, strip pitch, thermal and solutal Rayleigh numbers on the combined heat and mass transfer, particularly on the multiple steady motions, have been explored [10].

Observing from aforementioned studies, only the enclosed domain filling with porous medium is considered. Thinking essentially of actual engineering applications, such as food and grain storage, building construction elements, internal fluid motion could interact with ambient environment through openings or infiltrations, i.e., partial enclosures. In past decades, single component natural convection in partial enclosures has been investigated broadly, including inclination, port size, heating boundary conditions, fluid properties, coupling with radiation, etc [11–26].

In the present work, double diffusive natural convection in a cavity with multiple free openings, modeling the food and grain storages under natural environment, will be investigated numerically. To the authors' knowledge, this problem has never been studied. The porous medium considered here is modeled according to the Darcy–Brinkman formulation, which could account for the inertia effects and the no-slip boundary conditions on rigid

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doi:10.1016/j.applthermaleng.2010.01.009

Nomenclature

AR	aspect ratio (W/H)
d	size of port
D	mass diffusivity (dimensionless port size)
Da	Darcy number (K/H^2)
g	gravitational acceleration
H	height of the enclosure
k	thermal conductivity of the porous medium
K	permeability of the porous medium
Le	Lewis number (α/D)
M	dimensionless volumetric flow rate
N	buoyancy ratio
Nu	overall Nusselt number
p	fluid pressure
Pr	Prandtl number (ν/α)
Ra	thermal Rayleigh number
s	dimensional mass fraction
Sh	overall Sherwood number
T	temperature
u, v	velocity components
W	width of the enclosure
x, y	Cartesian coordinates

Greek symbols

α	thermal diffusivity
β_t	thermal expansion coefficient
β_s	expansion coefficient with mass fraction
ν	kinematic viscosity
ρ	fluid density
τ	dimensionless time
Ψ	dimensionless streamfunction
ξ	dimensionless heatfunction
η	dimensionless massfunction

Subscripts

L	left side
max, min	maximum, minimum
o	reference
s	solutal
t	thermal
T, R, B	top, right and bottom vents

Superscript

$*$	dimensional variable

boundaries [5,6,10,27]. Additionally, visualization of the heat and solute transports, using streamlines, heatlines and masslines [9,10,27–30], would be conducted in the present work.

In following sections, the physical model and mathematical formulation for the problem is first given. Subsequently, a numerical simulation of the full governing equations is carried out to study the transport structures and heat/mass transfer rates. Finally, the results from the numerical computations are discussed in details.

2. Physical model and problem statements

The physical domain under investigation is a two-dimensional fluid-saturated Darcy–Brinkman porous enclosure (see Fig. 1). The rectangular enclosure is of width W and height H, and the Cartesian coordinates (x, y), with the corresponding velocity components (u, v), are indicated herein. It is assumed that the third

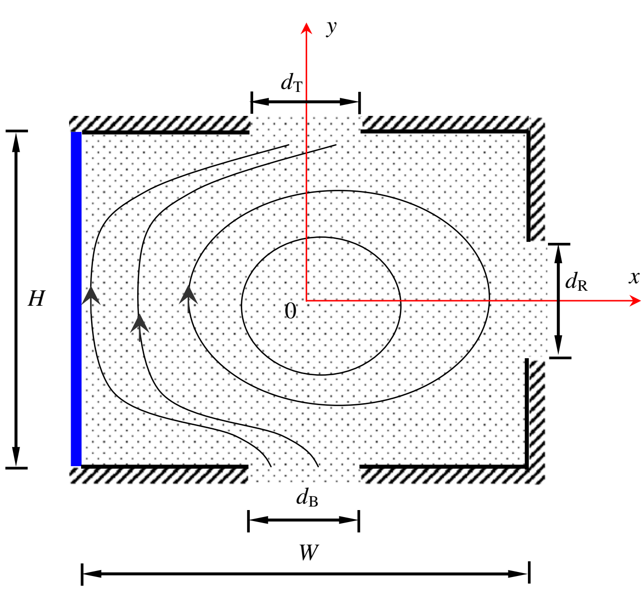

Fig. 1. Physical model and Cartesian ordinates of the present study.

dimension of the enclosure is large enough so that the fluid, heat and mass transports are two-dimensional. Three ports, respectively of size d_T, d_R, and d_B, are respectively centrally-imposed on the top, bottom and right boundaries of the enclosure, where ambient fluid could enter the enclosure or enclosed fluid could effuse into the ambient. The left wall maintains higher and constant temperature and concentration, t_1 and s_1, while the rest of cavity walls are insulated and impermeable. Ambient fluid reservoir is maintained lower temperature and concentration constants, t_0 and s_0. Gravity acts in the negative y-direction.

The porous matrix is assumed to be uniform and in local thermal and compositional equilibrium with the saturating fluid. Thermophysical properties are supposed constant. The flow is assumed to be laminar and incompressible. Viscous dissipation and porous medium inertia are not considered, and the Soret and Dufour effects are neglected. Density of the saturated fluid mixture is assumed to be uniform over all the enclosure, exception made to the buoyancy term, in which it is taken as a function of both the temperature t and concentration s through the Boussinesq approximation [13],

$$\rho = \rho_0[1 - \beta_t(t - t_0) - \beta_s(s - s_0)] \tag{1}$$

Where ρ_0 is the fluid density at temperature t_0 and concentration s_0, and β_t and β_s are the thermal and concentration expansion coefficients, respectively. Subscript 0 refers to the condition over the ambient fluid reservoir.

By employing the aforementioned assumptions into the macroscopic conservation equations of mass, momentum, energy and species, a set of dimensionless governing equations is obtained as,

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

$$\frac{\partial U}{\partial \tau} + \frac{\partial UU}{\partial X} + \frac{\partial VU}{\partial Y} = -\frac{\partial P}{\partial X} + \sqrt{\frac{Pr}{Ra}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \sqrt{\frac{Pr}{Ra}}\frac{U}{Da} \tag{3}$$

$$\frac{\partial V}{\partial \tau} + \frac{\partial UV}{\partial X} + \frac{\partial VV}{\partial Y} = -\frac{\partial P}{\partial Y} + \sqrt{\frac{Pr}{Ra}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) - \sqrt{\frac{Pr}{Ra}}\frac{V}{Da} + (T + NS) \tag{4}$$