Simulation of unsteady heat and mass transport with heatline and massline in a partially heated open cavity

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ABSTRACT

A computational work is performed to investigate the transient heat and mass transfer inside a ventilated enclosure. The enclosure has two ventilation ports as inlet and outlet. Three different configurations are tested according to location of outlet ports while location of inlet port is fixed. In case 1, the outlet port is located on the top of the left vertical wall, in case 2 at the right and case 3 at the middle of the ceiling. Finite element method is employed to solve the governing equations of flow, heat and mass transfer. Also, the heatline and massline techniques are used to visualize the heat and mass transfer patterns. Obtained results show the evolution of various contours of stream function, isotherms and iso-concentrations as well as various parameters such as Nu and Sc numbers. It is found in particular that in order to reach highest heat and mass transfer rates for $Gr = 10^7$, the outlet port should be located near the top of the left vertical wall. On the other hand, the effect of outlet location is insignificant for the lower values of Gr.

1. Introduction

Air-conditioning systems are very important on thermal comfort and life quality. Energy consumption is very high in these kinds of systems. Thus, the efficiency of the designed systems is a valuable subject for their sustainability and cost. In those systems, heat and mass transfer occurs in general simultaneously. Besides, the analysis of the flow distribution associated with the heat and mass transfer is very important for the design and efficiency of such AC systems.

The flow, heat and mass transfer in cavities with inlet and outlet ports are analyzed for these kinds of problems in various previous works. Liu et al. [1] studied the simultaneous transport of heat and moisture in a partially open enclosure with a thick wall. They used heatlines and masslines visualization techniques to simulate heat and moisture transport. They observed that the heat transfer potential, mass transfer potential, and volume flow rate can be promoted or inhibited. The effective parameters are wall materials and size as well as thermal and moisture Rayleigh number.

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Nomenclature

Br	buoyancy ratio
c	dimensional concentration of species
C	dimensionless species concentration
D	species diffusivity
g	gravitational acceleration
Gr	Grashof numbers
H	height of the cavity
h	sizes of inlet and outlet
L	length of the cavity
Le	Lewis number
L_s	length of the heat and mass sources
Nu	Nusselt number
n	unit normal to the surface
p	dimensional pressure
P	dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
Sh	Sherwood number
T	dimensional temperature
t	time
u, v	dimensional velocity components
$\bar{V}$	(U, V) dimensionless velocity components
x, y	dimensional Cartesian coordinates
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity
τ	dimensionless time
β_T	thermal expansion coefficient
β_c	compositional expansion coefficient
ν	kinematic viscosity
θ	dimensionless temperature
ρ	mixture density
ψ	streamfunction
Γ	general dependent variable
∇^2	Laplacian operator
ξ	heatfunction
ζ	massfunction

Subscripts

av	average
c	referring concentration
h	higher value
L	lower value
p	referring pressure
T	referring temperature
i	inlet

Transient laminar forced convection heat transfer leading to periodic state within a square cavity with inlet and outlet ports due to an oscillating velocity at the inlet port is presented by Saeidi and Khodadadi [2]. They indicated that the mean Nusselt numbers on the four walls clearly exhibit large amplitudes of oscillation and periodicity for St = 0.1 and increasing of St number, the amplitudes of oscillation on various walls are degraded. In another work, they presented forced convection results by investigating location of inlet and outlet ports [3]. Rahman et al. [4] studied the effects of heat generation and Reynolds and Prandtl numbers are studied for the same geometry [5]. Liu et al. [6] modeled numerically the indoor air quality with a new window-type air conditioner. They observed that the reduction of indoor pollutant levels can be accomplished either by increasing the fresh air ratio, or by decreasing the strength of indoor heating source. Oztop [7] worked on a mixed convection heat transfer in an enclosure with inlet and outlet ports and observed in particular that the location of the outlet port affects significantly the heat transfer and fluid flow. Besides, the inclination effects is an important parameter for natural

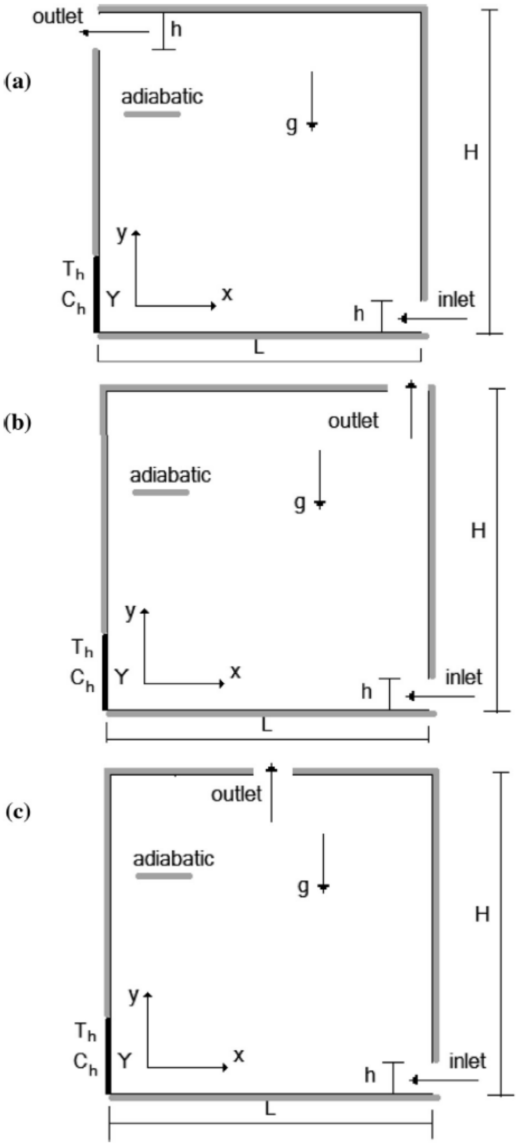

Fig. 1. Physical configuration for the problem with boundary conditions (a) case 1, (b) case 2, (c) case 3.

convection heat transfer in partially or fully open inclined cavities as indicated by Bilgen and Oztop [8]. Sourtiji et al. [9] observed that the oscillations of incoming flow in a cavity with inlet and outlet ports may represent a good way to improve the heat transfer.

Heatlines and masslines visualization techniques have been used in several studies to analyze the heat and mass transport characteristics. In this context, the study of Kimura and Bejan [10] may be the pioneer of this subject. Mobedi and Oztop [11] visualized the heat transport in a conjugate natural convection problem. They observed that using of heatline technique is the appropriate way to understand the heat transfer behavior in both solid and fluid. Heatline based heat flow visualization is analyzed by Basak et al. [12] in a square cavity. Zhao et al. [13] presented the heatlines, streamlines and masslines visualization in a square object inserted cavity. They indicated that the streamlines, heatlines and masslines provide a more practical way to visualize the results than the customary energetical systems.

Numerical visualization of heat and mass transport for convective heat transfer by streamlines and heatlines are studied by Deng and Tang [14]. Then, they extended this work to mixed convection heat transfer [15]. They conducted an optimization analysis on the ventilation system for different outlet location to simulate an air-conditioning system. Celik and Mobedi [16] performed visualization of heat flow in a vertical channel with fully developed mixed convection.

The finite element method is a powerful technique that has been used in many studies to solve and visualize flow with heat and mass transfer for regular and curvilinear geometries as [17–20]. It was used also to solve double-diffusive natural convection problems [21–23].

Stavrakakis et al. [26] developed a new model to optimize window design for thermal comfort in naturally ventilated buildings. They made a single-room, rural-type prototype to make tests. They used both CFD and Artificial Neural Networks (ANN). Finally, they obtained optimal window designs, which correspond to the best objective variables for both single and several activity levels. In their similar work [27] they made an optimization study for window-openings design. Other studies with ventilated buildings can be found in [28–30].

The main objective of the present work is to examine transient behavior of the heat and mass transfer due to mixed convection in a ventilated cavity with partially heated and humidified. Three different cases are tested according to location of outlet port while inlet port is fixed. Results will be presented for different Grashof numbers and dimensionless time. Also, as a novelty result time dependent heat and mass transport patterns will be discussed using heatline and massline techniques.

2. Considered problem

The study consists of the analysis of the two dimensional transient behavior of laminar mixed convective flow with heat and mass transfer in open cavities. Three different configurations are studied (Fig. 1). For all configurations, constant temperature and constant concentration are partially applied on the bottom left of the vertical wall of the cavity. All other boundaries are assumed adiabatic and impermeable (zero concentration gradient). The inlet port is located on the right bottom wall. In case 1, outlet hole is located on left wall near the ceiling, in case 2, outlet port is located on the right side of the ceiling. The outlet port is located on the middle of the ceiling in case 3.

3. Governing equations

The solution domain of the present study is given in Fig. 1(a)–(c). The governing equations are those expressing the conservation of mass, momentum, energy and concentration transports in the enclosure. The fluid and transported pollutant are assumed to be perfectly mixed inside the cavity. To simplify analysis, the following assumptions are made for this mixture

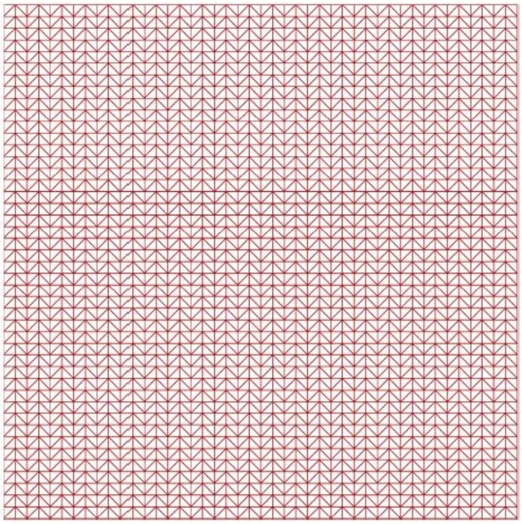

Fig. 2. Grid distribution of the considered geometry.

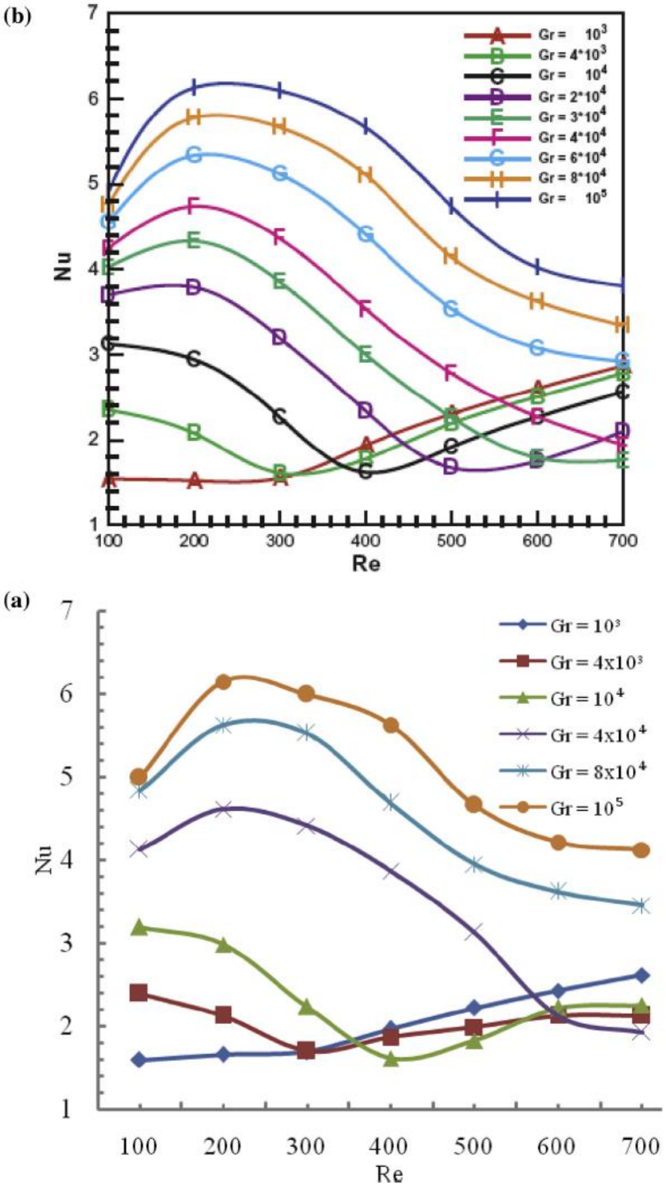

Fig. 3. Comparison of the (a) present model with (b) the results of Deng et al. [26].

inside the cavity: (i) the double-diffusive mixed convection is two-dimensional and unsteady; (ii) the mixture is Newton–Fourier fluid, which flows in laminar regime and does not experience any phase change; (iii) the mixture is incompressible but expands or contracts under temperature and/or concentration changes. Also, all thermo physical properties of the mixture are taken to be uniform overall the cavity, except for the density variation in the buoyancy term in Boussinesq approximation. The mixture density in the buoyancy term can thus be obtained [24] as $\rho = \rho_L[1 - \beta_T(T - T_L) - \beta_c(c - c_L)]$, where ρ_L, T_L, c_L are the reference density, temperature and concentration. According to Thermodynamics $\beta_T = -\frac{1}{\rho_L}(\frac{\partial\rho}{\partial T})_{P,c}$ and $\beta_c = -\frac{1}{\rho_L}(\frac{\partial\rho}{\partial c})_{P,T}$ are the volumetric thermal and concentration expansion coefficients respectively. In energy conservation analysis, it is assumed that thermal levels are small and similar enough so that the thermal radiation heat transfer between the heat source and the incoming mixture is negligible. The energy term due to viscous dissipation and change of temperature due to work of pressure forces are not considered. Besides, transfer of energy by inter-diffusion of species as well as Soret and Duffour effects are not considered here [25]. Taking into account the above mentioned assumptions the non-dimensional forms of the governing conservation equations are as follows:

$$\nabla \bar{V} = 0 \tag{1}$$

$$\frac{\partial \overline{V}}{\partial \tau} + (\bar{V} \cdot \nabla)\overline{V} = -\nabla P + \frac{1}{\mathrm{Re}}\nabla^2 \overline{V} + \frac{\mathrm{Gr}_T}{\mathrm{Re}^2}\left(\frac{\partial \theta}{\partial X} + \mathrm{Br}\frac{\partial C}{\partial X}\right) \tag{2}$$

$$\frac{\partial \theta}{\partial \tau} + \bar{V} \cdot \nabla \theta = \frac{1}{\mathrm{RePr}}\nabla^2 \theta \tag{3}$$

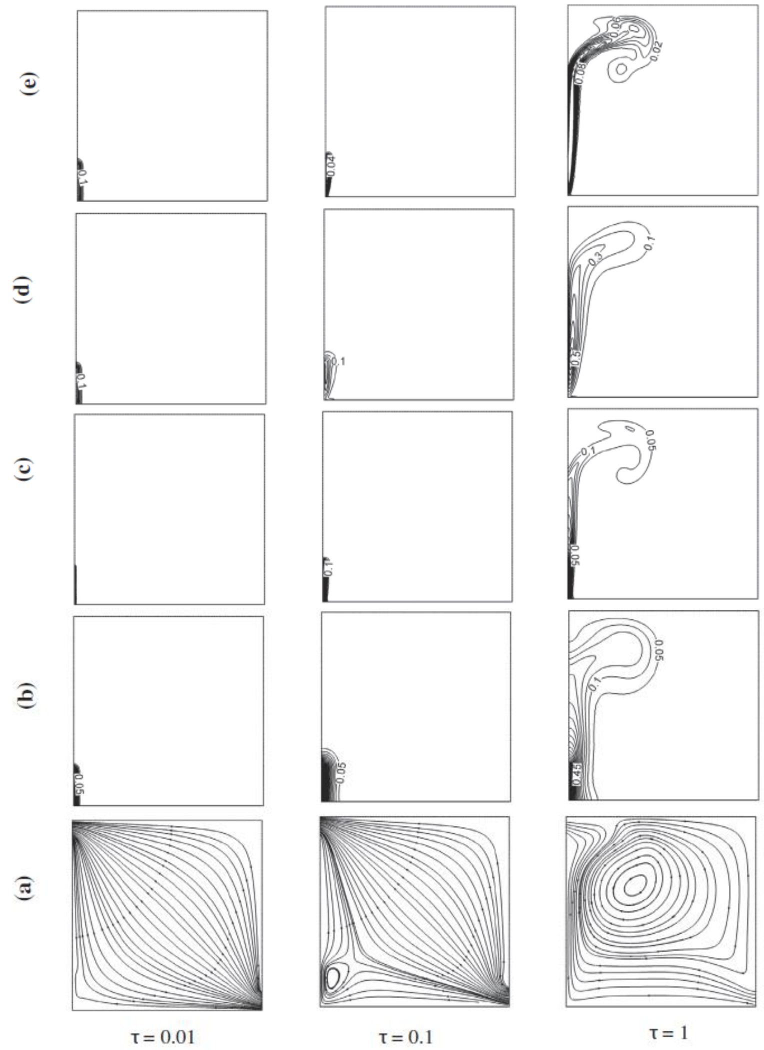

Fig. 4. Effect of dimensionless time τ on (a) streamlines, (b) isotherms, (c) iso-concentration, (d) heatline and (e) massline for the case 1 at $\mathrm{Gr} = 10^5$.

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