MIXED CONVECTION COUPLED TO SURFACE RADIATION IN A VENTED ENCLOSURE UNDER CONSTANT HEAT FLUX HEATING

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Abstract
The present work reports a numerical study of combined laminar mixed convection and surface radiation in a multiple vented rectangular enclosure uniformly heated from below with a constant heat flux. The purpose of this study is to examine the influence of the Reynolds number, $300 \le Re \le 5000$, and the emissivity of the walls, $0.15 \le \varepsilon \le 0.85$, on flow and thermal fields and heat transfer performance.

Keywords: *Mixed convection, surface radiation, multiple vented cavity, numerical study.*

1. Introduction
In many engineering systems with important heat generation, it is necessary to use an external ventilation to achieve higher thermal performance and evacuate the generated heat within the system in order to maintain it at its recommended working temperature and avoid serious overheating problems. Since natural convection is not able to provide cooling effectiveness, the mixed convection cooling mechanism has been recommended in such systems. An exhaustive review of the literature shows that the problem of mixed convection in ventilated cavities was examined by several authors and the references [1, 2] are quoted only by way of indication. However, the effect of radiation, due to its complexity, has been overlooked in the majority of the available studies in spite of its significant contribution to the overall heat transfer. To understand the dynamical behaviour of heat and fluid flow due to surface radiation, a number of works have been presented on natural convection inside rectangular cavites [3, 4]. In recent years the current interest has switched to complex cavities with obstructions in the form of solid bodies or fins or partial baffles. Indeed, considerable attention has been focused on coupled natural convection and surface radiation in partitioned cavities [5, 6]. Unfortunately, studies on mixed convection that involve surface radiation in vented enclosures seem to be relatively few in spite of their practical interest [7, 8]. Hence, the focus of this paper is to simulate numerically the interaction of mixed convection and surface radiation in a rectangular enclosure with multiple ventilation ports. The consequence of varying the Reynolds number (Re) and the emissivity of the walls (ε), on flow pattern, temperature field and heat transfer performance have been investigated and discussed.

2. Problem statement and mathematical modeling
The schematic view of the geometry considered in the study is presented in Fig. 1. It consists of a ventilated rectangular cavity having an aspect ratio $A = L'/H' = 2$ and uniformly heated with a constant heat flux from the bottom. The upper horizontal and right vertical walls are considered perfectly insulated, while the left side of the cavity is cooled with a uniform temperature. The physical system is submitted to an imposed ambient air stream through two openings located on the lower part at both right and left vertical walls. The forced flow leaves the cavity through an outflow opening placed at the middle of the top horizontal wall. The inner surfaces, in contact with the fluid, are assumed to be gray, diffuse emitters and reflectors of radiation with identical emissivities. The flow is assumed to be two-dimensional and laminar. The transparent fluid is incompressible and obeying the Boussinesq approximation. Under these assumptions, the corresponding set of differential equations using the vorticity-stream function formulation can be written in dimensionless form as follows:

$$\frac{\partial \Omega}{\partial t} + u\frac{\partial \Omega}{\partial x} + v\frac{\partial \Omega}{\partial y} = \frac{1}{Re}\left[\frac{\partial^2 \Omega}{\partial x^2} + \frac{\partial^2 \Omega}{\partial y^2}\right] + \frac{Ra}{Re^2\, Pr}\frac{\partial T}{\partial x} \quad (1)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{Re\,Pr}\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] \quad (2)$$

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = -\Omega \quad (3)$$

The radiosity method is used for the calculation of the radiative heat exchange between surfaces of the cavity. The non-dimensional radiosity equation for the i-th element of the enclosure may be written as:

$$J_i = \varepsilon_i \left(\frac{T_i}{T_0} + 1 \right)^4 + (1 - \varepsilon_i) \sum_{j=1}^{N} F_{ij} J_j$$

The dimensionless net radiative heat flux leaving the elementary surface S_i is given by:

$$Q_r = J_i - I_i = \varepsilon_i \left[\left(\frac{T_i}{T_0} + 1 \right)^4 - \sum_{j=1}^{N} F_{ij} J_j \right]$$

Where F and T_0 are the view factors and the dimensionless reference temperature, respectively.

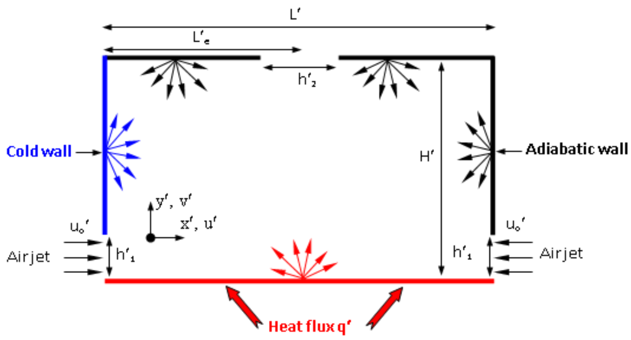

Fig.1: Schematic diagram of the studied configuration.

The appropriate boundary conditions used are as follows:

$u = v = 0$ on the rigid walls

$T = v = \Omega = 0$, $u = 1$ and $\Psi = y$ at the left inlet

$T = v = \Omega = 0$, $u = -1$ and $\Psi = -y$ at the right inlet

$T = 0$ on the left vertical cold wall

$$-\frac{\partial T}{\partial y} + N_r Q_r = 1 \quad \text{on the lower horizontal heated wall}$$

$$-\frac{\partial T}{\partial n} + N_r Q_r = 0 \quad \text{on the adiabatic walls}$$

"N_r" is the convection-radiation parameter and "n" indicates the outward normal to the considered adiabatic wall.

The average Nusselt numbers, characterizing the contributions of mixed convection and thermal radiation through the heated wall, are respectively defined by:

$$Nu_H(cv) = -\frac{1}{A}\int_0^A \frac{1}{T}\left(\frac{\partial T}{\partial y}\right)\bigg|_{y=0} dx \quad ; \quad Nu_H(rd) = \frac{1}{A}\int_0^A \frac{1}{T}(N_r Q_r)\bigg|_{y=0} dx \qquad (6)$$

The overall Nusselt number, Nu_H, is evaluated as being the sum of the corresponding convective and radiative Nusselt numbers; i.e. $Nu_H = Nu_H(cv) + Nu_H(rd)$.

3. Results and discussion

In the present work, the value of the Rayleigh number was maintained constant at $Ra = 5\times10^6$. This parameter induces values of the Richardson number, Ri, varying in the range [0.28; 77.16] for the considerd range of the Reynolds number ($300 \le Re \le 5000$). The specified range of the Richardson number corresponds to cases simulating natural convection, mixed convection and forced convection dominating regimes.

Typical streamlines and isotherms illustrating the radiation effect on the flow structure and temperature patterns are presented in Figs. 2a-2c for Re = 300 and various values of ε. In the absence of radiation effect, Fig. 2a shows that the forced flow enters horizontally through the two inlet openings and then ascends vertically at the middle of the cavity before leaving the latter through the outlet opening. Also, we note the existence of two closed cells surmounting the open lines of the forced flow. The formation of these cells, located in the corners of the upper part of the cavity, is due to the shear effect. The corresponding isotherms are tightened at the level of the heated bottom wall indicating a good convective heat exchange. From the temperature distribution, a thin horizontal thermal boundary layer is seen at the level of the heated wall. The heat provided by the heated horizontal wall is carried out vertically through the vertical corridor leading to the outlet of the cavity. Consecutively, a great part of the space offered in the cavity is at a uniform cold temperature. In the case of radiatively participating inner surfaces (ε = 0.15), it can be seen from Fig. 2b that the flow structure is affected. In fact, the right clockwise cell is divided into two cells separated by the open lines while the left cell becomes more distorted. A further increase of the emissivity to 0.85 leads to a complete disappearance of the closed cells located in the right part of the cavity (Fig. 2c) in favor of the open lines of the forced flow. This results from the aspiration of the injected flow under the effect of the buoyancy force which develops at the level of the vertical right wall heated under the effect of radiation. The cold zone space is seen to be reduced indicating the important role of radiation in the homogenization of the fluid temperature inside the cavity. This result is attributed to the heating of the adiabatic upper and left walls which present increasingly significant thermal gradients as the emissivity increases.

Variations, versus Re, of the average Nusselt numbers, resulting from contributions of convection and radiation and the overall Nusselt number, evaluated along the horizontal heated wall, are presented in Figs. 3a-3c for various values of ε. As shown in Fig. 3a, $Nu_H(cv)$ increases monotonously with Re either with or without radiation effect. The rate of this increase becomes very notable for Re > 1000. This tendency results from the flow intensification with the inertia effect, promoted by the increase of Re. For a fixed value of this parameter, the convection effect is clearly reduced, especially for low values of Re, when the emissivity of the walls is increased. The negative impact of radiation on the mixed convection is well known and it is confirmed here in the case of vented cavities. However, for higher values of Re, the convective component becomes insensitive to the radiation effect. The effect of walls emissivity on radiative heat transfer is presented in Fig. 3b in terms of Nu_H(rd) variations with Re for ε = 0.15, 0.5 and 0.85. Generally, it can be noted that, for a given value of Re, the increase of the emissivity leads to an important increase of the radiative heat transfer component. Alternatively, the effect of Re on Nu_H(rd) remains ver limited for weak or moderate value of ε. But for the highe value of the latter (ε = 0.85), Re contributes to enhanc Nu_H(rd) for predominant forced flow (Re > 1000). Th variations of the total Nusselt number with Re is presented in Fig. 3c. It shows the positive impact of Re and ε on th overall heat transfer.

4. Conclusion

The problem of mixed convection coupled with thermal radiation in a vented cavity has been investigated numerically. Results of the study reveal that radiation affects the flow structure and leads to a better homogenization of the temperature inside the cavity. Moreover, the radiation reduces the convective heat exchange for low values of Re and enhances the overall heat transfer.

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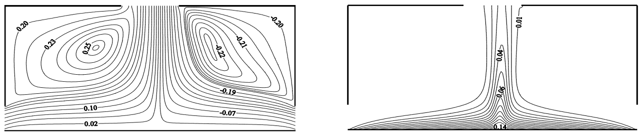
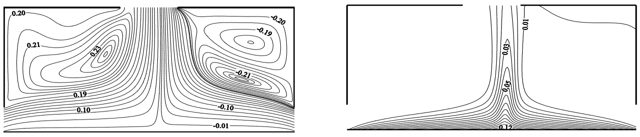
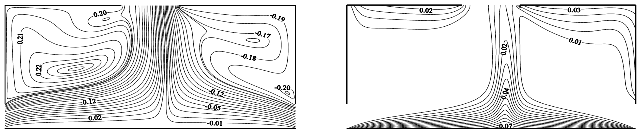


a) (Ψ_{min} = -0.218, Ψ_{max} = 0.250)



b) (Ψ_{min} = -0.207, Ψ_{max} = 0.231)



c) (Ψ_{min} = -0.201, Ψ_{max} = 0.224)

Fig.2: Streamlines and isotherms obtained for Re = 300 and various values of ε: a) ε = 0, b) ε = 0.15 and c) ε = 0.85.

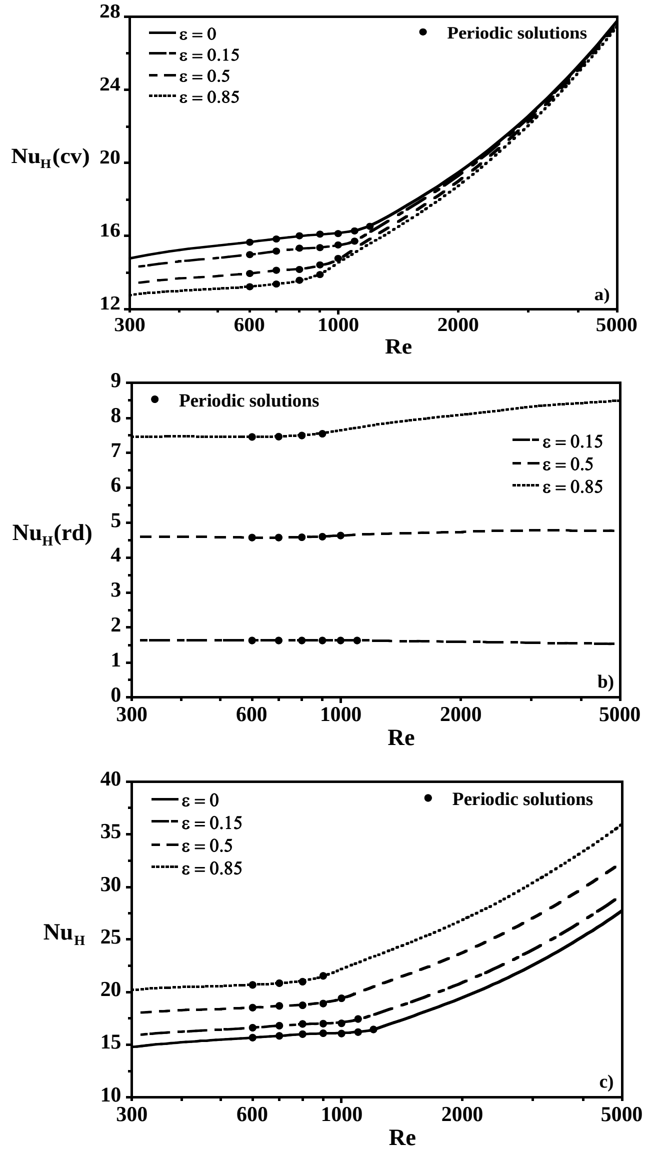


Fig.3: Variations, with Re, of the average Nusselt numbers on the heated wall for various values of ε: a) Nu_H(cv), b) Nu_H(rd) and c) Nu_H.