

Heat performance resulting from combined effects of radiation and mixed convection in a rectangular cavity ventilated by injection or suction

K. Ezzaraa¹, A. Bahlaoui¹, I. Arroub¹, A. Raji², M. Hasnaoui³ and M. Naïmi²

¹ Sultan Moulay Slimane University, Polydisciplinary Faculty, Department of Physics, Team of Applied Physics and New Technologies (EPANT), B. P. 523, Béni-Mellal 23000, Morocco.

² Sultan Moulay Slimane University, Faculty of Sciences and Technologies, Department of Physics, Laboratory of Flows and Transfers Modelling (LAMET), B. P. 523, Béni-Mellal 23000, Morocco.

³ Cadi Ayyad University, Faculty of Sciences Semlalia, Department of Physics, Laboratory of Fluid Mechanics and Energetics (LMFE), B.P. 2390, Marrakech, Morocco.

Abstract. In this work, we investigated numerically heat transfer by mixed convection coupled to thermal radiation in a vented rectangular enclosure uniformly heated from below with a constant heat flux. The fresh fluid is admitted into the cavity by injection or suction, by means of two openings located on the lower part of both right and left vertical sides. Another opening is placed on the middle of the top wall to ensure the ventilation. Air, a radiatively transparent medium, is considered to be the cooling fluid. The inner surfaces, in contact with the fluid, are assumed to be gray, diffuse emitters and reflectors of radiation with identical emissivities. The effects of some pertinent parameters such as the Reynolds number, $300 \leq Re \leq 5000$, and the emissivity of the walls, $0 \leq \varepsilon \leq 0.85$, on flow and temperature patterns as well as on the heat transfer rate within the enclosure are presented for the two ventilation modes (injection and suction). The results indicate that the flow and thermal structures are affected by the thermal radiation for the two modes of imposed flow. However, the suction mode is found to be more favorable to the heat transfer in comparison with the injection one.

1. Introduction

Mixed convection heat transfer in ventilated systems continues to be a fertile area of research, due to the interest of the phenomenon in many technological processes, such as the design of solar collectors, thermal design of buildings, air conditioning and recently the cooling of electronic circuit boards. However, the effect of the 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. Since moderate temperature differences involve significant radiation effects, the fact of neglecting the latter becomes non-realistic.

To understand the dynamical behaviour of heat and fluid flow due to surface radiation a number of computations have been recently presented on natural convection in closed or opened cavities. Related to the problem of differentially heated cavities, Bouafia et al. [1] performed a numerical study of the



interaction of natural convection with thermal radiation in a square cavity filled with air. Detailed analysis showed that the surface radiation reduces the convection heat transfer at the hot wall and increases it on the cold one. Also, the radiation promotes the occurrence of instabilities leading to an early transition to the unsteadiness. When the heating is from below, steady and unsteady analyses of surface radiation and natural convection in a cavity heated from below and cooled from above were carried out by Ridouane et al. [2]. They demonstrated the presence of multiple steady state solutions and they mentioned that the obtained steady state regimes is markedly affected by wall emissivity. In the case of side-vented open cavities, conjugate heat transfer by natural convection and radiation was studied experimentally by Ramesh and Merzkirch [3] where opening is localised on the top. They found that, for cavities with low emissive walls, natural convection was the dominant mode and with high emissive walls, both natural convection and radiation were competitive modes contributing equally to the total heat transfer. In this context, Singh et al. [4] performed a numerical study of the radiation and natural convection interactions in a tilted open cavity. The results showed that the heat transfer increases first and then decreases with decreasing the cavity tilt angle for all Rayleigh numbers and emissivity values.

Unfortunately, studies of mixed convection that involve surface radiation in vented enclosure seem to be relatively few in spite of its practical interest. When the ventilation is made by the inlet and outlet ports, Raji and Hasnaoui [5] numerically investigated the interaction between mixed convection and thermal radiation in a ventilated rectangular enclosure by considering two studied configurations (BT: assisting flows and TB: opposing flows). Results of the study showed that the radiation effect leads to a better homogenization of the temperature inside the cavity. It was also observed that in BT configuration due to the effect of radiation, the average temperature of enclosure increases, while the maximum temperature decreases. However, in the TB configuration, the radiation effect causes lowering of both mean and maximum temperatures. More recently, Bahlaoui et al. [6] carried out a numerical study of mixed convection combined with surface radiation inside a partitioned ventilated cavity. It was shown that the relative height of the adiabatic partition contributes to increase the radiative heat transfer component and leads to reduce the convective heat transfer component at the level of the heated wall.

Based on the available studies mentioned in the above literature review, the case of mixed convection in vented cavities with radiant walls hardly starts to arouse attention in spite of its obvious interest. However, it appears that no work was reported on combined mixed convection and surface radiation inside a rectangular enclosure with multiple ports and ventilated by two different modes (injection and suction). The present research is focused to studying such problem. Hence, the consequence of varying the controlling parameters such as the Reynolds number, the emissivity of the walls and the imposed flow mode, on flow and temperature fields and heat removal rate within the cavity have been investigated and discussed.

2. Problem description and mathematical formulation

The schematic diagram of the geometry considered in the study is presented in Fig. 1. It consists of a ventilated horizontal rectangular cavity having an aspect ratio $A = 2$ and uniformly heated from below with a constant heat flux. 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 which is admitted by injection (Fig. 1a) or suction (Fig. 1b) through two openings located on the lower part of both right and left vertical walls. A third opening is located on the middle of the upper wall for ventilation purposes. The fluid properties are evaluated at a cold temperature. The inner surfaces, in contact with the fluid, are assumed to be gray, diffuse emitters and reflectors of radiation with identical emissivities. The physical model is two-dimensional and the airflow is assumed to be laminar, incompressible and obeying the Boussinesq approximation. Therefore, using the following dimensionless variables:

$$A = L'/H' ; \quad B = h'/H' ; \quad x = x'/H' ; \quad y = y'/H' ; \quad u = u'/u'_0 ; \quad v = v'/u'_0 ; \quad t = t'u'_0/H' ;$$

$$T = \lambda (T' - T'_C)/q' H' ; \quad \Psi = \Psi'/u'_0 H' ; \quad \Omega = \Omega' H'/u'_0 ; \quad Pr = \nu/\alpha ; \quad Ra = g \beta q' H'^4 / \alpha \nu \lambda ;$$

$$Re = u'_0 H' / \nu$$

the corresponding set of differential equations, under the commonly assumptions, using the vorticity-stream function formulation can be written in dimensionless form as follows:

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

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

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

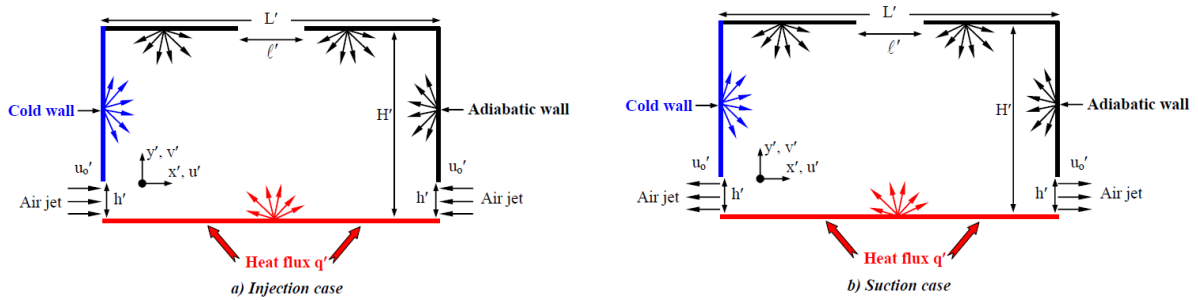


Figure 1. Schematic diagram of the studied configuration: a) Injection case and b) Suction case.

2.1. Boundary conditions

The common boundary conditions, in the dimensionless form, applied to the two ventilation modes can be defined by:

$u = v = 0$	on the rigid walls
$T = 0$	on the left vertical cold wall
$-\frac{\partial T}{\partial y} + N_r Q_r = 1$	on the lower horizontal heated wall
$-\frac{\partial T}{\partial n} + N_r Q_r = 0$	on the adiabatic walls
$\Psi = 0$	on the lower horizontal heated wall

"n" indicates the outward direction normal to the considered adiabatic wall.

The appropriate dimensionless boundary conditions related to the injection or suction cases can be written as:

Injection case :

$T = v = \Omega = 0, u = 1$ and $\Psi = y$	at the left inlet of the cavity
$T = v = \Omega = 0, u = -1$ and $\Psi = -y$	at the right inlet of the cavity
$\Psi = B$	between the left inlet port and the upper outlet port
$\Psi = -B$	between the right inlet port and the upper outlet port

For this injection mode, the boundary conditions are unknown at the upper outlet opening. Values of u, v, T, Ψ and Ω are extrapolated at each time step by considering zero second derivatives of these variables at the exit of the cavity.

Suction case :

$T = 0$	at the upper inlet port
$u = -1, v = 0, \Psi = -y$ and $\Omega = 0$	at the left outlet port
$u = 1, v = 0, \Psi = y$ and $\Omega = 0$	at the right outlet port
$\Psi = -B$	between the left outlet port and the upper inlet port
$\Psi = B$	between the right outlet port and the upper inlet port

For this suction mode, the boundary conditions for u , v , Ψ and Ω are unknown at the upper inlet opening whereas the temperature T is unknown at both left and right outlet openings. Similarly to the previous case, values of these variables are obtained at each time step by considering zero second derivatives of these variables at these openings.

2.2. Radiation equations

The enclosure analysis, with radiosity-irradiation formulation for the evaluation of the radiosities of all the walls elements, is used for making the calculation of the radiative heat exchange between the cavity and its surrounding. The walls of the cavity are subdivided into $N = 600$ elementary segments for the grid retained (201×101). Each segment is sufficiently small to be considered at uniform temperature. The shape factors between the isothermal elementary surfaces were determined by the Hottel's [7] crossed string method. The inner surfaces of the enclosure are assumed to be opaque and diffuse-grey. The openings of the cavity are assumed to be black at the ambient temperature. The general non-dimensional radiosity equation for the i^{th} element of the enclosure, which is filled with a radiatively non-participating medium, like air, may be written as:

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

Where $J_i = J'_i / \sigma T_C'^4$ and $T_o = \lambda T'_C / q' H'$ are the dimensionless radiosity and the dimensionless reference temperature, respectively.

2.3. Heat transfer

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

$$Nu_H(cv) = - \frac{1}{A} \int_0^A \frac{1}{T} \left(\frac{\partial T}{\partial y} \right) \bigg|_{y=0} dx \quad ; \quad Nu_H(rd) = \frac{1}{A} \int_0^A \frac{1}{T} (N_r Q_r) \bigg|_{y=0} dx \quad (5)$$

Where $N_r = \sigma T_C'^4 / q'$ and $Q_r = Q'_r / \sigma T_C'^4$ are the convection-radiation interaction parameter and the dimensionless net radiative heat flux, respectively.

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. Numerics

The set of coupled partial differential equations, Eqs. (1)-(3), were discretized using a finite differences method. The first and second derivatives of the diffusive terms were approached by central differences method while the advection terms are handled using a second order upwind scheme. Then, an alternating direction implicit (ADI) procedure was used to perform the time integration for the equations (1) and (2). At each time step, the Poisson equation, Eq. (3), was treated by using the point successive over-relaxation method (PSOR) with an optimum over-relaxation coefficient equal to 1.88 for the grid adopted in this study. The set of Eq. (4), representing the radiative heat exchange between the different sub-surfaces of the cavity, was solved by using the Gauss- Seidel method. The numerical computations were started using a pseudo-conductive regime or pure mixed convection solution as initial condition but the final stat is the same steady state solution.

4. Code validation and grid independence study

The numerical code was tested against the results of Wang et al. [8], in the case of a square cavity differentially heated, by simulating the mean total Nusselt numbers evaluated on the hot wall for Ra ranging from 10^4 to 10^6 and ε varying from 0 to 0.85. The maximum deviations observed remain within 1.62 % (Fig. 2). In addition, an overall energy balance for the system was systematically checked for all the computations. Thus, the energy released by the heating wall to the fluid is evaluated and compared with that leaving the cavity through the cold wall and the openings. The maximum relative variations generated are lower than 2 %.

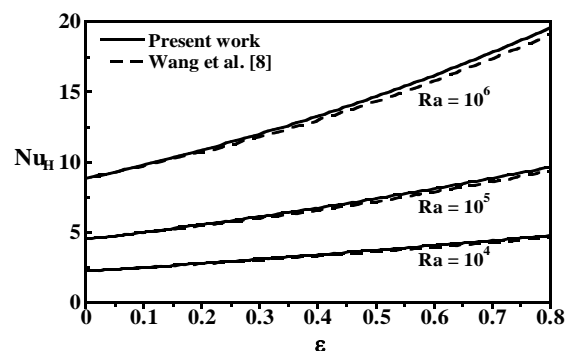


Figure 2. Effect of Ra and ε on the mean total Nusselt number, Nu_H , evaluated on the hot wall of a differentially heated square cavity for $T'_H = 298.5$ K and $T'_C = 288.5$ K.

The calculations were performed with a uniform grid of 201×101 for both x and y directions; grid selected was estimated to be appropriate for the present study since it permits a good compromise between the computational cost and the accuracy required. The results obtained with this grid were comparable to those obtained with a finer grid of 281×141 . In fact, the refinement of the grid to 281×141 involves maximum variations lower than 0.86 % and 1.37 % in terms of Ψ_{\max} and Nu , respectively (Table 1).

Table 1. Grid sensitivity check on the obtained results for $Ra = 5 \times 10^6$ ($Nr = 2.02$) and different values of Re and ε .

	Re = 300				Re = 1500			
	$\varepsilon = 0.15$		$\varepsilon = 0.85$		$\varepsilon = 0.15$		$\varepsilon = 0.85$	
Grids	Nu_H	Ψ_{\max}	Nu_H	Ψ_{\max}	Nu_H	Ψ_{\max}	Nu_H	Ψ_{\max}
201×101	15.882	0.231	20.220	0.224	19.101	0.236	24.761	0.233
281×141	16.086	0.231	20.433	0.225	19.362	0.238	25.048	0.235

5. Results and discussion

In the present study, the value of the temperature of the ambient imposed flow was considered constant at $T'_C = 298.15$ K. The fixed value of Rayleigh number ($Ra = 5 \times 10^6$), retained in this work, induces automatic values of the parameters Nr and To equal to 2.02 and 0.704, respectively. Also, the relative height of the vertical openings, h , and the relative length of the upper horizontal opening, λ , are maintained constants at $1/5$ and $2/5$ respectively.

Typical streamlines and isotherms illustrating radiation effect on the flow structure and temperature patterns, in the injection case, are presented in Figs. 3a-3b for $Re = 300$ and various values of ε . In the absence of radiation effect ($\varepsilon = 0$), Fig. 3a shows that the forced flow enters horizontally through the two vertical inlet openings and then ascends vertically at the middle of the cavity before leaving the latter through the upper outlet opening. Also, it is seen the existence of two closed cells surmounting

the open streamlines. 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. In addition, a thin horizontal thermal boundary layer is observed near the heated wall. Consecutively, a great part of the space offered in the cavity is at a uniform cold temperature. A progressive increase of the emissivity up to 0.85 (highly emissive walls), as shown in Fig. 3b, leads to a complete disappearance of the closed cell located in the right part of the cavity in favor of the open streamlines 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. This behavior is attributed to the heating of the adiabatic upper and right walls which present increasingly significant thermal gradients as the emissivity increases.

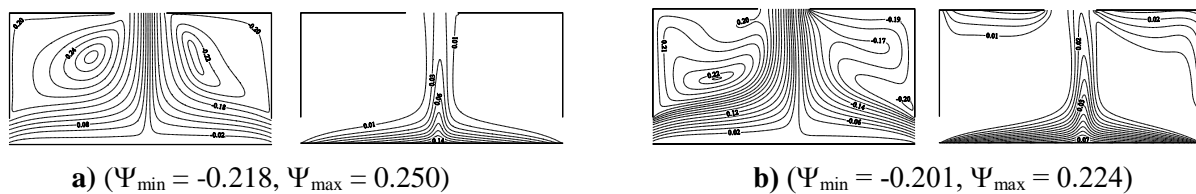


Figure 3. Streamlines and isotherms obtained, in the injection mode, for $Re = 300$ and various values of ε : a) $\varepsilon = 0$ and b) $\varepsilon = 0.85$.

In the case of the suction mode, streamlines and isotherms, illustrating the radiation effect on the flow structure and temperature distribution within the cavity, are presented in Figs. 4a-4b, for $Re = 300$ and various values of ε . Hence, Fig. 4a, obtained for $\varepsilon = 0$, shows that the flow descends vertically from the upper horizontal inlet and then leaves the cavity horizontally through the vertical two outlets. The structure is characterized by the formation, under the shear effect, of two big closed cells surmounting the open streamlines. These cells are straight and large in size and intensity compared to those presented in the injection mode (see Fig. 3a). The corresponding isotherms illustrate a very limited thermal boundary layer. Consequently, the heat released by the bottom hot wall is quickly and directly transferred to the exit through the thermal boundary layer without ascending under the buoyancy forces effect. It results from this behavior that the suction mode is thermally strong. By increasing progressively ε up to 0.85 (Fig. 4b), the left closed cell is reduced in size and intensity in favor of a small convective cell generated at the upper left corner of the cavity and whose the formation is due essentially to the growing natural convection effect involved by the heating of the upper wall under the radiation effect. In the other hand, the cold zone is relatively reduced.

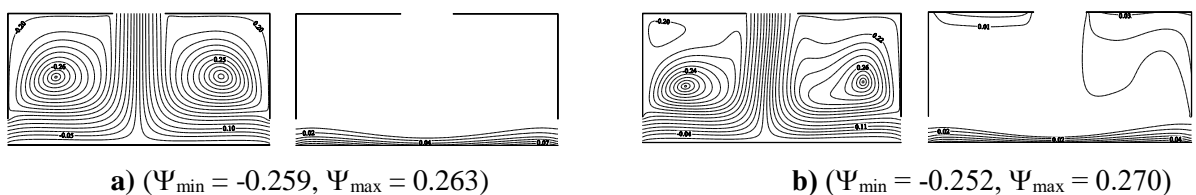


Figure 4. Streamlines and isotherms obtained, in the suction mode, for $Re = 300$ and various values of ε : a) $\varepsilon = 0$ and b) $\varepsilon = 0.85$.

Variations versus Re of the total Nusselt number are presented in Fig. 5. The results show increasing tendencies of Nu_H with Re and ε for the two ventilation types. Quantitatively, in the injection case, for $\varepsilon = 0.85$, improvements in terms of total heat transfer due to surface radiation is about 36 % and 29 % for $Re = 300$ and 5000 respectively in comparison with the reference case corresponding to $\varepsilon = 0$. Moreover, with respect to the injection mode, the enhancement of heat transfer achieved by the suction mode is very important. For instance, for $\varepsilon = 0.85$ and $Re = 5000$, passing

from the injection mode to the suction one, Nu_H increases from 35.9 to 66.4 which corresponds to an enhancement of the heat transfer by about 84.9 %.

The contribution of radiation to the total heat transfer through the heated wall of the cavity is quantified by presenting in Fig. 6 the evolution of the ratio $Nu_H(rd)/Nu_H$ with Re for various value of ε in both injection and suction cases. It is seen from the figure that, for a given ε , the contribution of radiation decreases, in generally, by increasing Re . However, despite this decrease, the contribution of radiation remains important, especially for moderate and high values of ε . More precisely, the maximum contribution of the radiative component reached in the injection / (the suction) mode for $\varepsilon = 0.85$ and $Re = 300$ is about 36.88 % / (34.36 %) respectively. Finally, it should be noted that the injection mode is more favorable to the contribution of radiation in comparison with the suction mode.

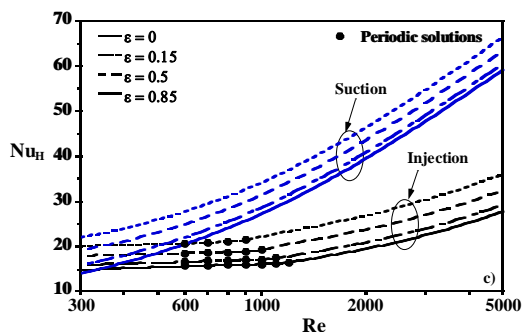


Figure 5. Variations, with Re , of the average total Nusselt number on the heated wall for various values of ε in both injection and suction modes

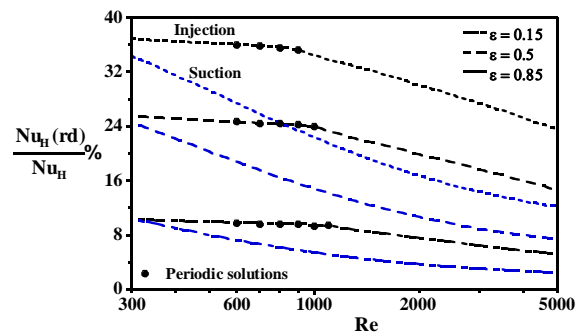


Figure 6. Contribution of radiation evaluated at the heated wall, as a function of Re , to the overall heat transfer for various values of ε in both injection and suction modes.

6. Concluding remarks

In the present work a numerical study was carried out to examine laminar mixed convection coupled to thermal radiation in a vented cavity totally heated from below. The study is conducted by considering two modes of imposed external flows (injection and suction). The obtained results reveal that the surface radiation alters widely the flow and temperature patterns, contributes to the temperature homogenization within the cavity and enhances the overall heat transfer. Also, it is found that the injection mode favors the contribution of radiative component but the suction mode is more efficient than the injection mode by leading to more total heat transfer across the cavity even with or without radiation.

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