Thermal Science - Online First

Online First contains the manscripts of articles that have been accepted for publication but have not yet appeared in the paper journal. They have been peer reviewed and edited to the journal's usual standards. Online First articles should be cited by their digital object identifiers (DOIs) which are given for every article. Manuscripts of the papers can be changed after technical and language corrections in the process of preparing computer layout for hard copy priniting.

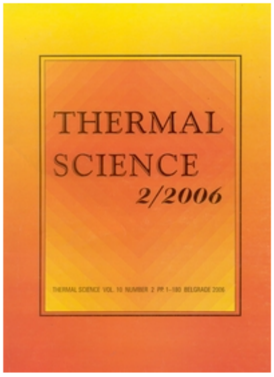
2018 2017 2016

Papers Accepted in 2018

Nesrine Rachedi, Madiha Bouafia, Messaoud Guellal, Saber Hamimid

EFFECT OF RADIATION ON THE FLOW STRUCTURE AND HEAT TRANSFER IN A TWO-DIMENSIONAL GRAY MEDIUM

abstract + pdf pdf download doi: https://doi.org/10.2298/TSCI180108117R



About the journal
Editorial policy
Instructions for authors

⊟All issues
- ⊟2018 OnLine-First
  - Issue 00
- ⊞2018
- ⊞2017 OnLine-First
- ⊞2017
- ⊞2016 OnLine-First
- ⊞2016
- ⊞2015
- ⊞2014
- ⊞2013
- ⊞2012
- ⊞2011
- ⊞2010
- ⊞2009
- ⊞2008
- ⊞2007
- ⊞2006
- ⊞2005
- ⊞2004
- ⊞2003
- ⊞2002

Publisher Info

Title:	Thermal Science
Web address:	http://thermalscience.vinca.rs
ISSN:	0354-9836
eISSN:	2334-7163
First published:	1997
Frequency:	six times a year
On-line first:	✓
Subject:	physical sciences; energy technologies and mining
Description:	The main aims of Thermal Science is to publish papers giving results of the fundamental and applied research in different, but closely connected fields: fluid mechanics (mainly turbulent flows), heat transfer, mass transfer, combustion and chemical processes, in single, and specifically in multi-phase and multi-component flows, and in high-temperature chemically reacting flows, and in processes present in thermal engineering, energy generating or consuming equipment, process and chemical engineering equipment and devices, ecological engineering. The important characteristic of the journal is the orientation to the fundamental results of the investigations of different physical and chemical processes, always jointly present in real conditions, and their mutual influence. To publish papers written by experts from different fields: mechanical engineering, chemical engineering, fluid dynamics, thermodynamics and related fields. To inform international scientific community about the recent,
Publisher:	VINČA Institute of Nuclear Sciences
Publisher address:	Mike Petrovića Alasa 12, 11000 Beograd, Vinča, Serbia
Impact factor:	**1.431** (2017) **1.093** (2016) **0.939** (2015) **1.222** (2014) **0.962** (2013) **0.838** (2012) **0.779** (2011) **0.706** (2010) **0.407** (2009)

Effect of radiation on the flow structure and heat transfer in a two-dimensional gray medium
Rachedi Nesrine, Bouafia Madiha, Guellal Messaoud, Hamimid Saber
Thermal Science, 2018 OnLine-First (00):117-117
Details Full text (1249 KB) https://doi.org/10.2298/TSCI180108117R

Thermal Science 2018 OnLine-First Issue 00, Pages: 117-117
https://doi.org/10.2298/TSCI180108117R
Full text (1249 KB)

Effect of radiation on the flow structure and heat transfer in a two-dimensional gray medium

Rachedi Nesrine, Bouafia Madiha, Guellal Messaoud, Hamimid Saber

A numerical study of combined natural convection and radiation in a square cavity filled with a gray non-scattering semi-transparent fluid is conducted. The horizontal walls are adiabatic and the vertical are differentially heated. Convection is treated by the finite volumes approach and the discrete ordinate method is used to solve radiative transfer equation using S6 order of angular quadrature. Representative results illustrating the effects of the Rayleigh number, the optical thickness and the Planck number on the flow and temperature distribution are reported. In addition, the results in terms of the average Nusselt number obtained for various parametric conditions show that radiation modifies significantly the thermal behavior of the fluid within the enclosure.

Keywords: natural convection, volumetric radiation, Planck number, optical thickness, semi-transparent medium

EFFECT OF RADIATION ON THE FLOW STRUCTURE AND HEAT TRANSFER IN A TWO-DIMENSIONAL GRAY MEDIUM

Nesrine RACHEDI[a], Madiha BOUAFIA[b], Messaoud GUELLAL[a*] and Saber HAMIMID[a]

[a] Laboratoire de Génie des Procédés Chimiques, Université Ferhat Abbas Sétif-1, Sétif 19000, Algeria
[b] Laboratoire de Mécanique et Energétique d'Evry, Université d'Evry, 91020 Evry Cedex, France

A numerical study of combined natural convection and radiation in a square cavity filled with a gray non-scattering semi-transparent fluid is conducted. The horizontal walls are adiabatic and the vertical are differentially heated. Convection is treated by the finite volumes approach and the discrete ordinate method is used to solve radiative transfer equation using S6 order of angular quadrature. Representative results illustrating the effects of the Rayleigh number, the optical thickness and the Planck number on the flow and temperature distribution are reported. In addition, the results in terms of the average Nusselt number obtained for various parametric conditions show that radiation modifies significantly the thermal behavior of the fluid within the enclosure.

Keywords*: natural convection; volumetric radiation, Planck number, optical thickness, semi-transparent medium*

1. Introduction

The study of combined natural convection radiation in two-dimensional semi-transparent medium is widely encountered in engineering and remains a topical subject for scientists and researchers in various fields such as furnace design, heat exchangers, cooling of electronic components, nuclear reactors, etc. A fair amount of research in this area was devoted to the heat transfer in semi-transparent media. Lauriat [1] studied natural convection in the presence of radiation by considering a gray gas contained in a vertical two-dimensional cavity of elongation between 5 and 20. P1 approximation of spherical harmonics method was used for the radiative problem. The same problem was modeled by Yucel et al. [2] using the discrete ordinate method. The investigation involves a square cavity whose four walls are black. The Rayleigh number was fixed at 5×10^6 and the variation of the optical thickness was taken into account. Draoui et al. [3] studied the Rayleigh number effect using P1 approximation of spherical harmonics method. The emissivity is equal to 0 for adiabatic walls and 1 for isothermal walls. Colomer et al. [4] also addressed combined natural convection and radiation considering both transparent and participating media in a three-dimensional differentially heated cavity. They solved the radiative transfer equation using the discrete ordinates method and conservation equations of natural convection by means of segregated SIMPLE-like algorithm. In his work, A. Ibrahim [5] was interested in the impact of radiation on the natural convection in a square cavity filled with binary gaseous mixture where at least one component radiates

* Corresponding author, e-mail: mguellal@univ-setif.dz

in the infrared. S. Meftah et al. [6] studied the effects of non-gray gas radiation on laminar double diffusive convection in a square cavity filled with air-CO_2 mixtures when vertical walls are maintained at different temperatures and concentrations. Moufekkir et al. [7] used hybrid thermal lattice Boltzmann method (HTLBM) to study numerically natural convection and volumetric radiation in an isotropic scattering medium within a heated square cavity. Momentum and energy equations are solved by finite difference method (FDM), while S8 quadrature of the discrete ordinates method (DOM) has been used to solve the radiative transfer equation. Chaabane et al. [8] developed an algorithm for solving natural convection coupled to radiation in a two-dimensional cavity containing an absorbing, emitting and diffusing medium. The radiative transfer equation is solved using control volume finite element method; the density, velocity and temperature fields are determined using the two double population Lattice Boltzmann equation.

Kolsi et al. [9] studied the effect of radiation and aspect ratio on 3-D natural convection of the $LiNbO_3$ in vertically lengthened enclosures for, Ra = 10^5 and for various optical properties. The conservation equations, expressed according to the vorticity-stream function formulation, and the radiative transfer equation are resolved by volume control method and the FTn finite volume method respectively. The obtained numerical results showed that the radiation-conduction parameter affects considerably the principal flow structure.

Other works dealing with combined natural convection-surface radiation in differentially heated cavities have received considerable attention in the literature, either in the case of Boussinesq approximation [10-13] or under Low Mach Number conditions [14-15].

The purpose of this work is to study the effects of volumetric radiation on the flow and heat transfer of a gray non-scattering semi-transparent fluid within a differentially heated square cavity. A parametric study of impact of main variables involved in the phenomenon will be also conducted.

2. Physical model and governing equations

2.1. Governing equations

The studied physical system is illustrated in fig. 1. It is a square cavity filled with a semi-transparent medium assumed to be homogeneous, incompressible, laminar, gray and non-scattering. The two vertical walls are black ($\varepsilon_{1,2} = 1$) and maintained at different temperatures T_C and T_H ($T_C < T_H$), while the two horizontal walls are reflective ($\varepsilon_{3,4} = 0$) and perfectly insulated. It will be further assumed that the temperature differences in the flow domain under consideration are small enough to justify the employment of the Boussinesq approximation. The medium is initially at rest and at a uniform temperature $T_0 = (T_H + T_C)/2$.

The equations to be solved are based on the balance laws of mass, momentum and energy, as well as the radiative transfer equation (RTE) which provides the term of radiative source to be inserted into the energy equation.

Theses equations are converted into the non-dimensional form by using the non-dimensional variables:

$L = L'/4\sigma T_0^4$, $P = P'/\rho V_0^2$, $Q_r = Hq_r/k(T_H - T_C)$

$T = (T' - T_0)/\Delta T$, $t = t' V_0/H$,

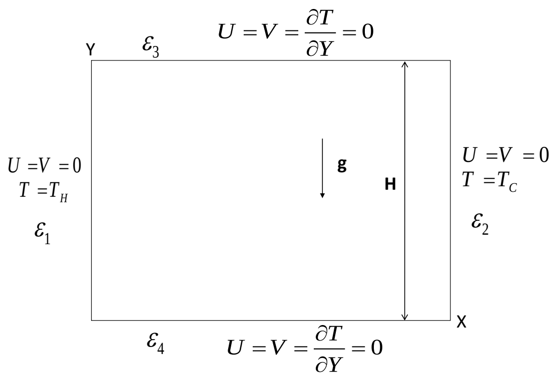


Figure 1. Physical geometry and boundary conditions

$U = uH/\left(\nu\sqrt{Ra}\right)$, $V = vH/\left(\nu\sqrt{Ra}\right)$, $X = x/H, Y = y/H$,$\theta_0 = T_0/(T_H - T_C)$

Considering the above assumptions, the governing equations for an unsteady two-dimensional problem can be written in dimensionless form as:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\sqrt{Ra}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (2)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{\sqrt{Ra}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{1}{Pr}T \quad (3)$$

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \frac{1}{Pr\sqrt{Ra}}\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) - \frac{1}{Pr\sqrt{Ra}}\, div(Q_r) \quad (4)$$

With:

Prandtl number: $Pr = \nu/\alpha$

Rayleigh number: $Ra = g\beta\Delta T H^3/\nu\alpha$

The source term in the energy equation is equal to the divergence of the radiative heat flux representing the radiative exchange rate in the cavity which is calculated by the following equations:

$$\mu\left(\frac{\partial L}{\partial X}\right) + \eta\left(\frac{\partial L}{\partial Y}\right) + \tau L = \frac{\tau}{4\pi}\left(1 + \frac{T}{\theta_0}\right)^4 \quad (5)$$

$$div(Q_r) = \frac{\tau}{Pl}\theta_0\left[\left(1 + \frac{T}{\theta_0}\right)^4 - \int_{4\pi} L d\Omega\right] \quad (6)$$

Pl is the Planck number defined as:

$Pl = k/4H\sigma T_0^3$

Equation (5) represents the radiative transfer equation (RTE) for a two-dimensional absorbing, emitting and non-scattering medium.

$L(X, Y, \vec{\Omega})$ is the dimensionless radiation intensity at position (X, Y) in the direction $\vec{\Omega} = \mu\vec{i} + \eta\vec{j}$.

2.2. Boundary conditions

The boundary conditions applied on the horizontal walls are described by the equations:

$$\mathrm{U} = \mathrm{V} = 0, -\frac{\partial \mathrm{T}}{\partial \mathrm{Y}} + \varepsilon_3 \frac{\theta_0}{\mathrm{Pl}}\left[\frac{1}{4}\left(1+\frac{\mathrm{T}}{\theta_0}\right)^4 - \mathrm{Q_{inc}}\right] = 0 \text{ at } Y = 0 \text{ and for } 0 \leq \mathrm{X} \leq 1 \quad (7)$$

$$\mathrm{U} = \mathrm{V} = 0, \frac{\partial \mathrm{T}}{\partial \mathrm{Y}} + \varepsilon_4 \frac{\theta_0}{\mathrm{Pl}}\left[\frac{1}{4}\left(1+\frac{\mathrm{T}}{\theta_0}\right)^4 - \mathrm{Q_{inc}}\right] = 0 \text{ at } Y = 1 \text{ and for } 0 \leq \mathrm{X} \leq 1 \quad (8)$$

$\mathrm{Q_{inc}}$ is the incident radiation flux obtained by:

$$\mathrm{Q_{inc}}(\mathrm{X},0) = \sum_{\eta_m<0} |\eta_m| \omega_m \mathrm{L}(\mathrm{X},0) \text{ at } \mathrm{Y}=0 \quad (9)$$

$$\mathrm{Q_{inc}}(\mathrm{X},1) = \sum_{\eta_m>0} |\eta_m| \omega_m \mathrm{L}(\mathrm{X},1) \text{ at } \mathrm{Y}=1 \quad (10)$$

In this investigation, adiabatic horizontal walls are completely reflective ($\varepsilon3 = \varepsilon4 = 0$). The adiabacity condition is reduced to:

$$-\frac{\partial \mathrm{T}}{\partial \mathrm{Y}} = 0 \quad \text{at } \mathrm{Y}=0 \text{ for } 0 \leq \mathrm{X} \leq 1 \quad (11)$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{Y}} = 0 \quad \text{at } \mathrm{Y}=1 \text{ for } 0 \leq \mathrm{X} \leq 1 \quad (12)$$

The boundary conditions on the vertical walls are:

$$\mathrm{U} = \mathrm{V} = 0, \mathrm{T} = \mathrm{T_H} \text{ at } \mathrm{X}=0 \text{ and for } 0 \leq \mathrm{Y} \leq 1 \quad (13)$$

$$\mathrm{U} = \mathrm{V} = 0, \mathrm{T} = \mathrm{T_C} \text{ at } \mathrm{X}=1 \text{ and for } 0 \leq \mathrm{Y} \leq 1 \quad (14)$$

The radiative boundary conditions are:

$$\mathrm{L}(\mathrm{X},0) = \frac{\varepsilon_3}{4\pi}\left(1+\frac{\mathrm{T}(\mathrm{X},0)}{\theta_0}\right)^4 + \frac{1-\varepsilon_3}{\pi}\mathrm{Q_{inc}}(\mathrm{X},0) \text{ at } \mathrm{Y}=0 \text{ and for } \eta < 0 \quad (15)$$

$$\mathrm{L}(\mathrm{X},1) = \frac{\varepsilon_4}{4\pi}\left(1+\frac{\mathrm{T}(\mathrm{X},1)}{\theta_0}\right)^4 + \frac{1-\varepsilon_4}{\pi}\mathrm{Q_{inc}}(\mathrm{X},1) \text{ at } \mathrm{Y}=1 \text{ and for } \eta > 0 \quad (16)$$

$$\mathrm{L}(0,\mathrm{Y}) = \frac{\varepsilon_1}{4\pi}\left(1+\frac{\mathrm{T}(0,\mathrm{Y})}{\theta_0}\right)^4 + \frac{1-\varepsilon_1}{\pi}\mathrm{Q_{inc}}(0,\mathrm{Y}) \text{ at } \mathrm{X}=0 \text{ and for } \mu < 0 \quad (17)$$

$$\mathrm{L}(1,\mathrm{Y}) = \frac{\varepsilon_2}{4\pi}\left(1+\frac{\mathrm{T}(1,\mathrm{Y})}{\theta_0}\right)^4 + \frac{1-\varepsilon_2}{\pi}\mathrm{Q_{inc}}(1,\mathrm{Y}) \text{ at } \mathrm{X}=1 \text{ and for } \mu > 0 \quad (18)$$

With:

$$\mathrm{Q_{inc}}(0,\mathrm{Y}) = \sum_{\mu_m<0} |\mu_m| \omega_m \mathrm{L}(0,\mathrm{Y}) \text{ at } \mathrm{X}=0 \quad (19)$$

$$\mathrm{Q_{inc}}(1,\mathrm{Y}) = \sum_{\mu_m>0} |\mu_m| \omega_m \mathrm{L}(1,\mathrm{Y}) \text{ at } \mathrm{X}=1 \quad (20)$$

One obtains for vertical walls ($\varepsilon_1 = \varepsilon_2 = 1$):

$$\mathrm{L}(0,\mathrm{Y}) = \frac{1}{4\pi}\left(1+\frac{\mathrm{T}(0,\mathrm{Y})}{\theta_0}\right)^4 \text{ at } \mathrm{X}=0 \quad (21)$$

$$\mathrm{L}(1,\mathrm{Y}) = \frac{1}{4\pi}\left(1+\frac{\mathrm{T}(1,\mathrm{Y})}{\theta_0}\right)^4 \text{ at } \mathrm{X}=1 \quad (22)$$

And for horizontal walls ($\varepsilon_3 = \varepsilon_4 = 0$):

$$\mathrm{L}(\mathrm{X},0) = \frac{1}{\pi}\mathrm{Q_{inc}}(\mathrm{X},0) \text{ at } \mathrm{Y}=0 \text{ and for } \eta < 0 \quad (23)$$

$$\mathrm{L}(\mathrm{X},1)=\frac{1}{\pi}\mathrm{Q}_{\mathrm{inc}}(\mathrm{X},1) \text{ at } Y=1 \text{ and for } \eta>0 \tag{24}$$

2.3. Heat transfer

The average non-dimensional heat transfer rate in terms of convective and radiative Nusselt numbers, are respectively defined as:

$$\mathrm{Nu}_{\mathrm{cv}}=\int_0^1-\left(\frac{\partial \mathrm{T}}{\partial \mathrm{X}}\right)_{\mathrm{X}=0,1}\mathrm{dY} \tag{25}$$

$$\mathrm{Nu}_{\mathrm{r}}=\frac{\theta_0}{\mathrm{Pl}}\int_0^1\left[\frac{1}{4}\left(1+\frac{\mathrm{T}}{\theta_0}\right)^4-\mathrm{Q}_{\mathrm{inc}}\right]_{\mathrm{X}=0,1}\mathrm{dY} \tag{26}$$

The summation of the previous expressions gives the following expression for the global averaged Nusselt number:

$$\mathrm{Nu}_{\mathrm{t}}=\mathrm{Nu}_{\mathrm{cv}}+\mathrm{Nu}_{\mathrm{r}} \tag{27}$$

3. Numerical procedure

The numerical solution of the governing differential equations (1)-(4) is obtained by a finite volume technique using staggered arrangement. The discretization in time is done by a second-order backward Euler scheme in which the diffusive and viscous linear terms are implicitly treated while the convective non-linear terms are explicitly treated using an Adams-Bashforth extrapolation. The spatial discretization is based on a non-uniform grid refined in the vicinity of the vertical walls. A technique derived from the classical projection method is employed to solve the coupling between pressure and velocity. The Poisson equations for the pressure correction in the projection method are solved by standard multigrid techniques [15].

The numerical resolution of RTE (5) for a given direction Ω_m is performed using the discrete ordinates method DOM [16]:

$$\mu_m\frac{\partial L_m}{\partial X}+\eta_m\frac{\partial L_m}{\partial Y}+\tau L_m=\tau L_b \tag{28}$$

With: $L_b=\frac{1}{4\pi}\left(1+\frac{T}{\theta_0}\right)^4$

The integration of the radiative transfer equation (28) on control volume $\Delta V = \Delta X\ \Delta Y$ gives:

$$\mu_m\Delta Y\left(L_{m,E}-L_{m,W}\right)+\eta_m\Delta X\left(L_{m,N}-L_{m,S}\right)+\tau\Delta V L_{m,P}=\tau\Delta V L_b \tag{29}$$

μ_m and η_m are the direction cosines in X and Y directions repectively.

$L_{m,P}$, $L_{m,E}$, $L_{m,W}$, $L_{m,N}$, $L_{m,S}$ represent the radiation intensity at the center P and in the four directions (East, West, North, South) respectively. Radiation intensities are known on faces W and S and unknown at the center (P) and on faces E and N.

Two interpolation relationships are needed to eliminate $L_{m,E}$ and $L_{m,W}$, thereby allowing to calculate $L_{m,P}$. They are expressed as:

$$L_{m,P}=L_{m,W}+a\left(L_{m,E}-L_{m,W}\right)=L_{m,S}+b\left(L_{m,N}-L_{m,S}\right) \tag{30}$$

Coefficients a and b take values 0.5 or 1 according to the scheme type:

a = b = 0.5 for diamond scheme

a = b = 1 for step scheme.

Equation (29) becomes then :

$$L_P = \frac{\left(\frac{\mu m \Delta X}{a}\right) L_W + \left(\frac{\eta m \Delta Y}{b}\right) L_S + \tau \Delta V L_b}{\left(\frac{\mu m \Delta X}{a}\right) + \left(\frac{\eta m \Delta Y}{b}\right) + \tau \Delta V} \quad (31)$$

The step scheme was used in the present work. The coupling between the convection and radiation is ensured by the divergence of the radiative heat flux. This term source is proportional to the fourth power of the temperature. The solution of this type of problem, guaranteeing the convergence of the computation process, requires the linearization of the temperature using the Taylor series.

Grid independence study is performed to analyse the influence of the grid size on the computational results. Table 1 shows the average total and radiative Nusselt numbers according to the number of mesh nodes, for Pr = 0.71, Ra=5.10^6, τ = 1, Pl=0.1 and θ_0 = 1.5. It appears that the solution becomes independent of grid size at 161x161.

Table 1 . Grid size effect on the average Nusselt (total and radiative)

	33×33	57×57	97×97	129×129	161×161	257×257
Nu_T	13.32	13.32	12.98	12.96	12.58	12.58
Nu_r	4.563	4.4561	4.481	4.470	4.2	4.3

4. Results and discussions

In order to verify the developed numerical code, a comparison of our results with the literature was performed, by considering the total Nusselt number along the hot wall. Calculations were carried out for Pr = 0.71, Ra=5.10^6, τ = 1 and θ_0 = 1.5. Table 2 shows a good agreement with results of Moufekkir et al. [7].

It is interesting to note that laminar flow assumption was adopted by several previous studies working in the same conditions: Ra = 510^6, Pr=0.71 [2, 5, 6, 7**].**

Table 2. Total Nusselt number on the hot wall (Pr = 0.71, Ra=5.10^6, τ = 1 and θ_0 = 1.5)

Pl	Present study (uniform grid)	Present study (non-uniform grid)	Moufekkir et al. [7] (uniform grid)
0.1	12.58	12.01	12.069
1	7.800	7.752	7.729
10	7.273	7.226	7.314
100	7.258	7.253	7.273

To analyze the effects of the Planck number Pl, the optical thickness τ, and the Rayleigh number Ra, on the heat transfer and fluid flow in in steady-state conditions, we consider the following parameters: Pr = 0.71, Pl = 0.1....100,τ =0....5,Ra= 10^4..10^6 and θ_0= 1.5 .

The condition of stability is verified by examining the time evolution of temperature and velocity fluid for Pl=0.02, τ=1 and Ra=5.10^6 (fig. 2). The results obtained in unsteady state revealed that there is a great fluctuation at the beginning of the regime, and the transition to the steady state occurs beyond a time of 50, from which the flow becomes stable.

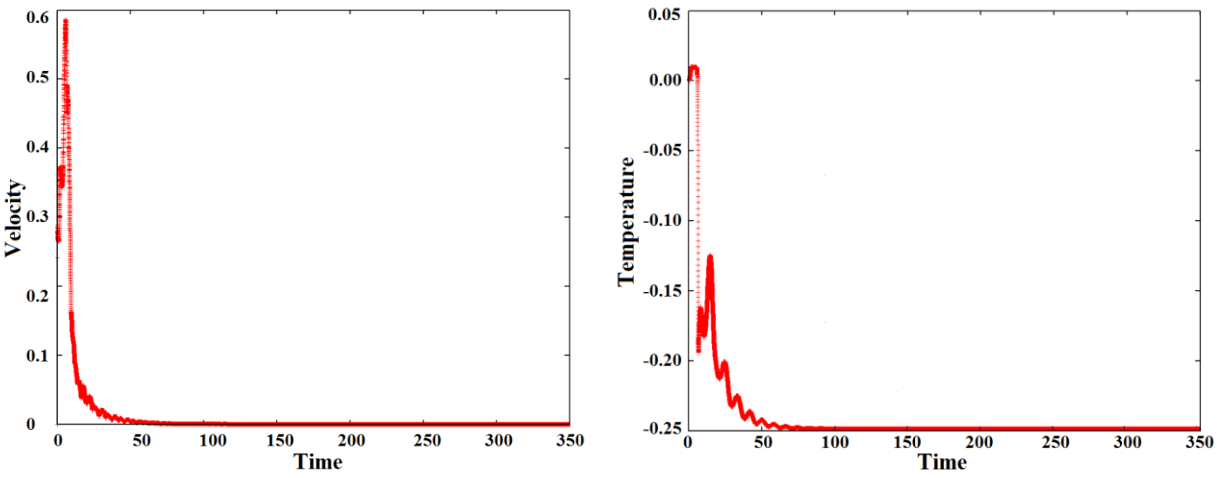
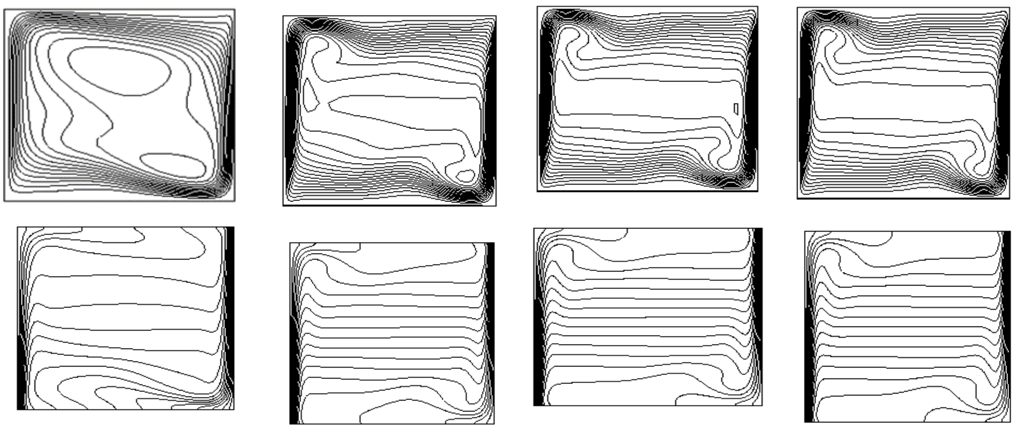


Figure 2. Variation of fluid temperature and velocity vs time

4.1. Effect of Planck number

The fixed parameters of simulation are Ra = 5.10^6, τ = 1. However, to examine the impact of the Planck number, we consider different values of Pl number varying from 0.1 to 100. At low Planck number (Pl = 0.1), the streamlines have a two-cell shape indicating a two asymmetrical secondary flows. With increasing Pl, cells are decomposed into S-shape indicating a unicellular flow in the core of the cavity (fig. 3). The flow and temperature fields present symmetrical structure with respect to the cavity center, indicating therefore a similar behavior of the fluid when the heat transfer is governed by pure natural convection.



Pl=0.1 Pl=1 Pl=10 Pl=100

Figure 3. Streamlines (top) and temperature contours (bottom)

The influence of the Planck number on the temperature and velocities is highlighted in fig. (4-5). It is observed that the decrease in the Planck number causes an intensification of the temperature and velocity gradients near the active walls. Vertical and horizontal profiles show that the Planck number increases the stratification in the cavity core (fig. 4) and reduces the amplitude of horizontal velocity (fig. 5).

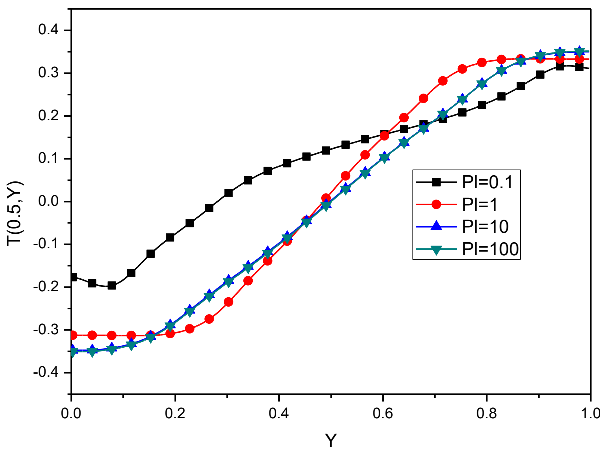


Figure 4. Cross-section of the temperature at mid-plane cavity X= 0.5

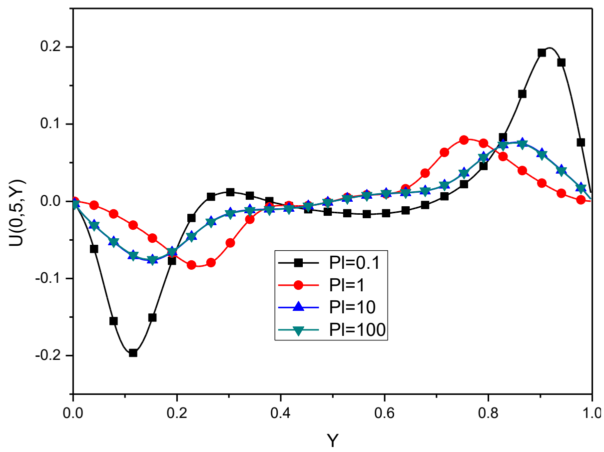


Figure 5. Horizontal velocity at the vertical cross-section X = 0.5

Figure 6 illustrates the variation of average total and radiative Nusselt numbers on the hot wall for different values of Planck number. It is worth noting that the Planck number Pl, also known as conduction-radiation parameter, expresses the ratio of conduction to radiation effects. We can note that the increase in the values of Planck number, leads to decrease in the average total Nusselt number. The same behavior is observed for the average radiative Nusselt number. Heat transfer is dominated by radiation when the Planck number is low.

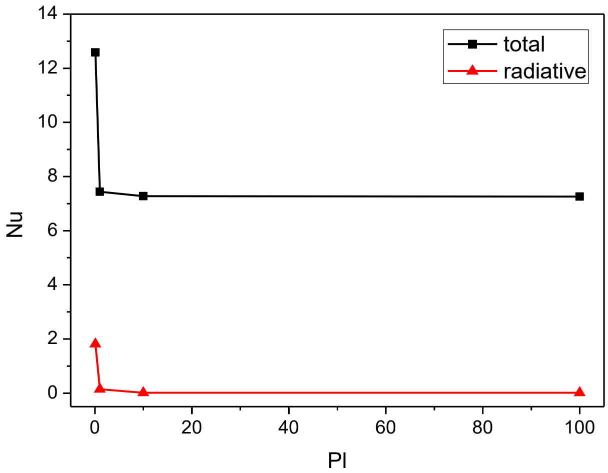


Figure 6. Variations of the average total and radiative Nusselt numbers as a function of Pl

4.2. Effect of the optical thickness

The effect of the optical thickness τ on temperature contours and streamlines is displayed in fig. 7. A strong deformation on the temperature distribution is observed when τ increases. For low values of the optical thickness, a recirculation flow appears near the horizontal boundary layers. However, the recirculation movements on the vicinity of the cavity walls tend to disappear with increasing the optical thickness. A large temperature gradient is noticed near to the boundary layer of cold wall. This is can be explained by the fact that the medium is more opaque and the radiation effect is stronger. We can note that the symmetrical nature of the flow is strongly broken in the presence of radiation.

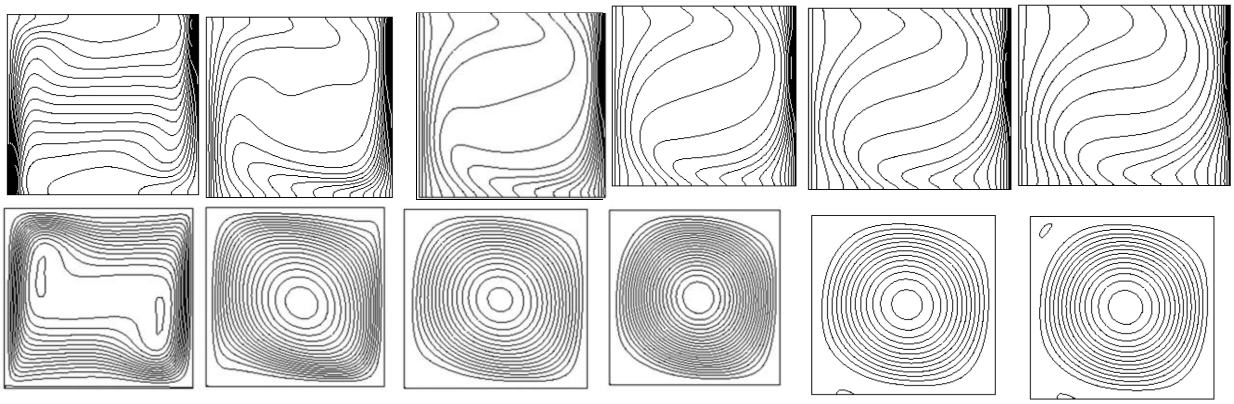


Figure 7. Temperature contours (top) and streamlines (bottom)

Figure 8 shows the variation of average total Nusselt number on the hot wall according to the optical thickness τ. With increasing of the optical thickness, the Nusselt number decreases indicating a significant heat exchange for a thicker medium. Figures 9 and 10 illustrate the variations of temperature as a function of optical thickness τ. Temperature profiles at mid-plane and mid-height cavity are greatly influenced by the radiation. It can be seen for a large optical thickness (τ> 0.5), temperature profiles depend slightly on τ.

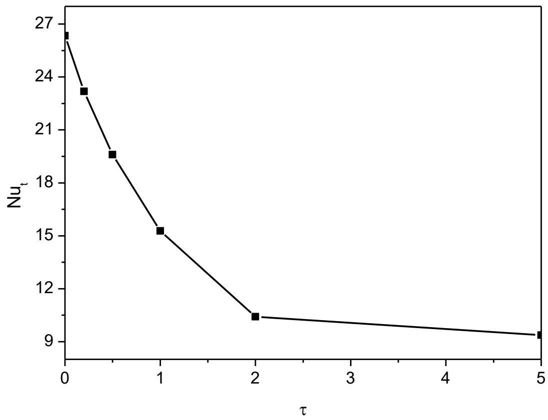


Figure 8. Variations of the average total Nusselt number as a function of optical thickness

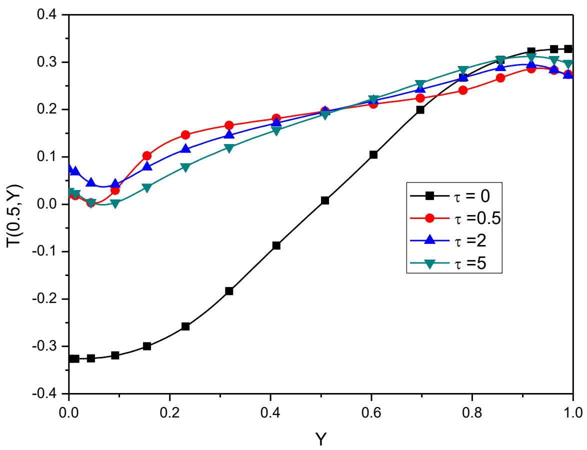


Figure 9. Cross-section of the temperature at mid-plane cavity for Ra=5.10^6 and Pl=0.02

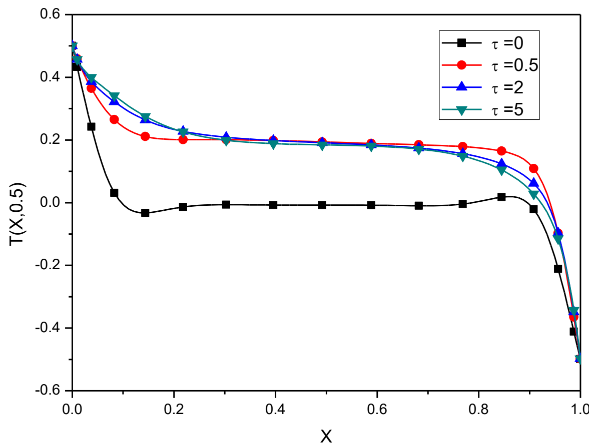


Figure 10. Cross-section of the temperature at mid-height cavity for Ra=5.10^6 and Pl=0.02

Analysis of fig. 11 and 12 shows that the maximum values of the horizontal and vertical velocities are strongly influenced by the optical thickness. An increase in the maximum velocity values can also be seen when τ increases.

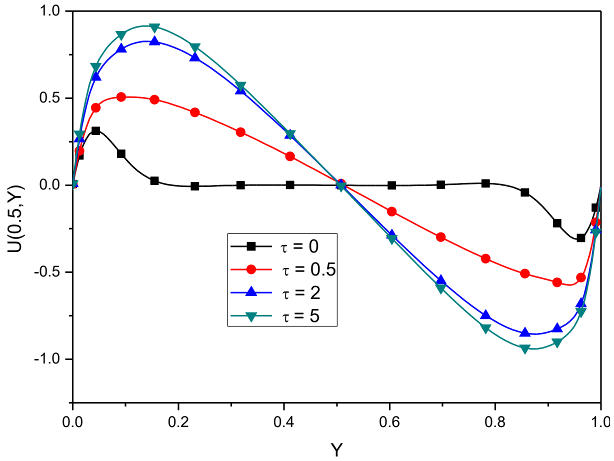


Figure 11. Horizontal velocity at the vertical cross-section for Ra = 5.10^6 and Pl = 0.02

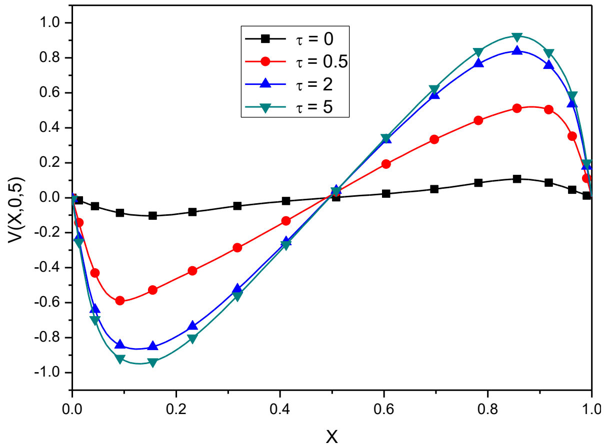


Figure 12. Vertical velocity at the horizontal cross-section for Ra = 5.10^{6}and Pl = 0.02

4.3. Effect of Rayleigh number

Another aim of this study is to examine the effect of Rayleigh number on the flow and heat transfer in presence of radiation (τ = 1). Computations are carried out for different values of Rayleigh number ($10^3 \leq Ra \leq 10^6$) and Pl = 0.02. Results obtained in terms of streamlines and isotherms are plotted in fig. 13. For low values of Ra, intensity of circulation is low, streamlines are circular, and isotherms tend to be parallel to active walls because heat transfer is done by conduction. Aside from a slight reduction in recirculation intensity at the core of the cavity, the effect of radiation on streamlines is not significant. The reduction of temperature gradients gives an indication of the importance of the radiative flux. For a large Rayleigh number, the isotherms move in a counterclockwise direction and become almost horizontal in the cavity core. The temperature contours show the increase of temperature gradient near cold wall due to the radiative exchange. At the core region, the presence of radiation leads to a homogenization of the temperature within the cavity.

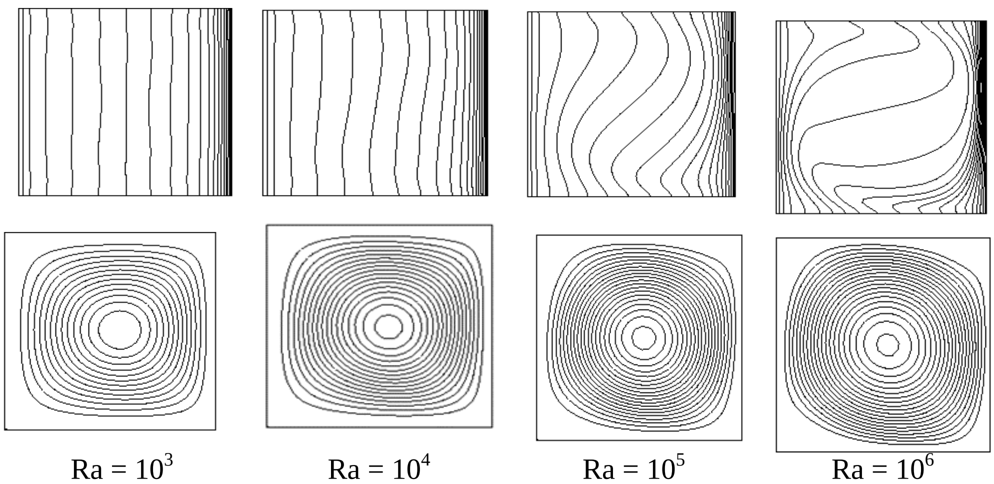


Figure 13. Isotherms (top) and streamlines (bottom) as a function of Ra for Pl =0.02.

As shown in fig. 14, the results in term of heat exchange reveal that the Nusselt number increases with increasing Rayleigh number and decreases with the augmentation of the optical thickness.

Velocity components are plotted in fig. 15 across the mid-planes. Unlike the case of low Rayleigh values, the flow velocity becomes large when Ra increases and the circulation becomes strong near the vertical walls. Due to the presence of radiation, the temperature and velocities profiles are no longer symmetric and the fluid is less stratified at the center region of the cavity (fig. 15and 16).

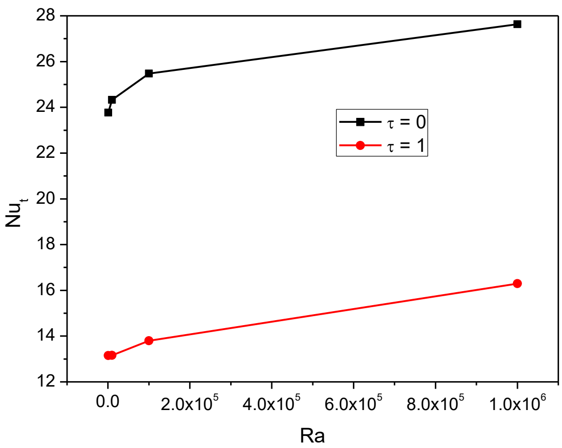


Figure 14. Variation of average total Nusselt number on the hot wall as a function of Rayleigh

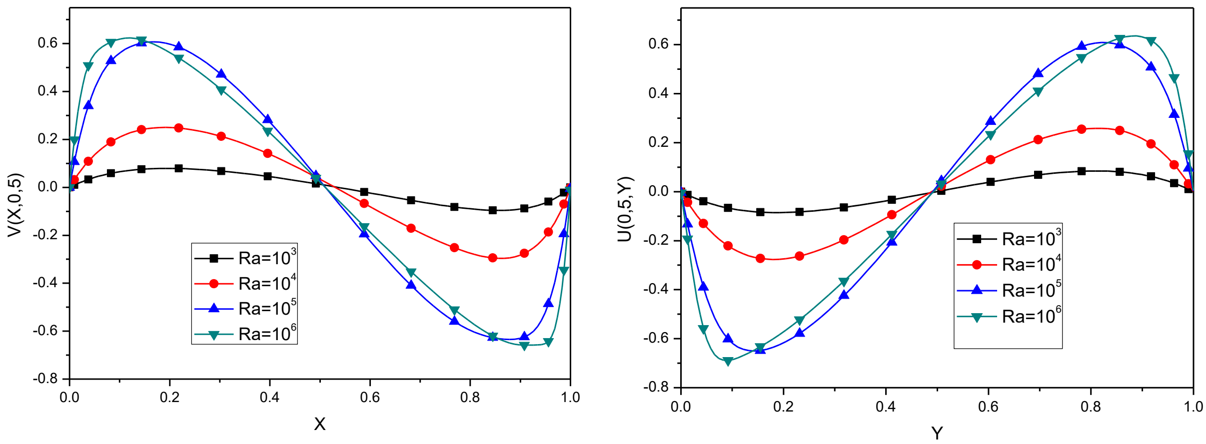


Figure 15. Profiles of vertical (left) and horizontal (right) velocities across the mid-planes for different Rayleigh numbers, Pl = 0.02 and τ = 1.

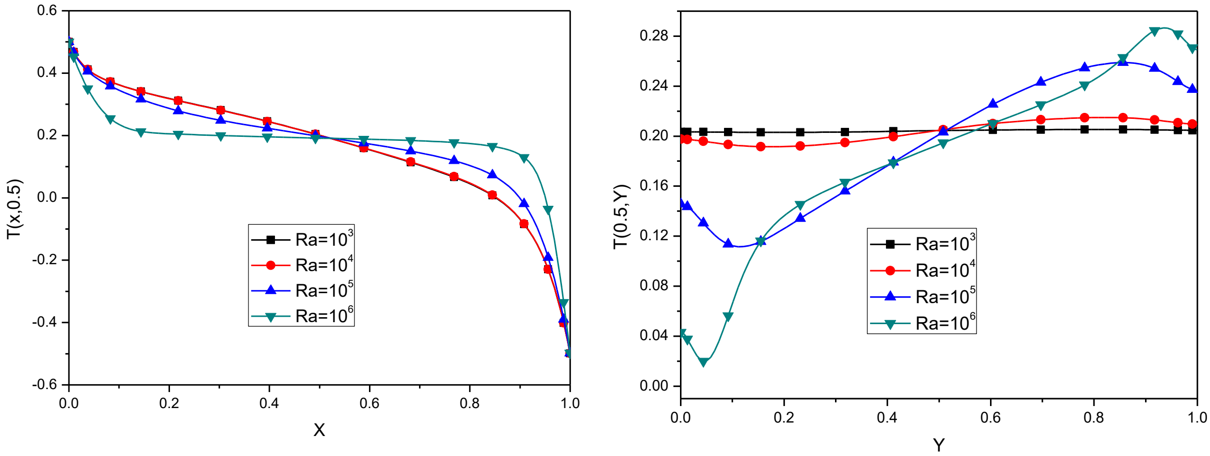


Figure 16. Temperature profiles at mid-height (left) and mid-plane (right) for different values of Rayleigh number and Pl = 0.02.

5. Conclusions

In the present paper, computations have been carried out to study the combined natural convection and volumetric radiation in a differentially-heated cavity filled with a gray non-scattering semi-transparent medium. In the presence of radiation, isotherms and streamlines are strongly affected and velocities are intensified particularly for large Rayleigh number. The study shows that in radiatively thin media, multicellular structures can appear within the cavity. The decrease in the value of Planck number leads to an intensification of the temperature and velocity gradients near the active walls. It is also noted that the Planck number increases the stratification in the cavity core and reduces the velocity amplitude.

Nomenclature

Cp	specific heat capacity [$Jkg^{-1}K^{-1}$]
g	gravitational acceleration, [ms^{-2}]
k	thermal conductivity,[$Wm^{-1}K^{-1}$]
L	dimensionless radiation intensity,[-]
L_b	radiation intensity of the black body,[Wm^{-2}]
H	dimension of the enclosure,[m]
Nu	average Nusselt number, [-]
P	dimensionless pressure , [-]
Pr	Prandtl number ($= \nu/\alpha$), [-]
Pl	Planck number ($= k/4H\sigma T_0^3$), [-]
q_r	radiative heat flux [Wm^{-2}]
Q_r	dimensionless radiative heat flux, [-]
Q_{inc}	dimensionless incident radiative flux, [-]
Ra	Rayleigh number ($= g\beta\Delta TH^3/\nu\alpha$), [-]
T	dimensionless temperature, [-]
t	dimensionless time, [-]
u, v	dimensional velocity-components, [ms^{-1}]
U, V	dimensionless velocity-component, [-]
X, Y	dimensionlesscoordinates, [-]
x, y	cartesiancoordinates[m]

Greeksymbols

α	thermal diffusivity, ($= k/\rho Cp$), [ms^{-1}]
β	thermal expansion coefficient,[K^{-1}]
ε	emissivity, [-]
κ	absorption coefficient [m^{-1}]
ν	kinematicviscosity,[m^2s^{-1}]
ρ	fluiddensity[kgm^{-3}]
σ	Stefan-Boltzmann constant,[W/mK]
μ, η	direction cosines
ω_m	weight in the direction Ω_m
τ	optical thickness $\tau = H\kappa$
θ_0	dimensionless reference temperature,($= T_0/(T_H - T_C)$), [-]

Subscripts

‘	dimensional variables
cv	Convective
0	reference state
C	Cold
H	Hot
r	Radiative
t	Total

References

[1] Lauriat, G., Combined radiation-convection in gray fluids enclosed in vertical cavities, *J. Heat Transfer*, 104 (1982),*4*, pp. 609-615

[2] Yücel, A., et.*al.*, Natural convection and radiation in a square enclosure, *Numer. Heat Transfer A-Appl.*, 15 (1989), 2,pp. 261-278

[3] Draoui, A., et.*al.*, Numerical analysis of heat transfer by natural convection and radiation in participating fluids enclosed in square cavities, *Numer. Heat Transfer A-Appl.*, 20 (1991), *2*, pp. 253-261

[4] Colomer, G., et. *al.*, Three-dimensional numerical simulation of convection and radiation in a differentially heated cavity using the discrete ordinates method, *Int. J. Heat Mass Transfer*, 47 (2004), 2, pp. 257-269

[5] Ibrahim, A., Coupling of natural convection and radiation in absorbing-emitting gas mixtures (in French language), Ph. D. thesis, University of Poitiers, France, 2010

[6] Laouar-Meftah, S., et. *al.*, Comparative Study of Radiative Effects on Double Diffusive Convection in Non gray Air-CO_2 Mixtures in Cooperating and Opposing Flow, *Math. Probl. Eng.*, (2015), pp. 1-17

[7] Moufekkir, F., et. *al.*,Numerical prediction of heat transfer by natural convection and radiation in an enclosure filled with an isotropic scattering medium, *J. Quant. Spectrosc. Ra*, 113 (2012), 13, pp. 1689-1704

[8] Chaabane, R., et. al., Numerical study of transient convection with volumetric radiation using an hybrid lattice Boltzmann BGK-control volume finite element method, *J. Heat Transfer*, 139 (2017), 9, pp.1-7

[9] Kolsi, L., et. al.,, Combined radiation-natural convection in three-dimensional verticals cavities, *Therm. Sci.*, 15 (2011), suppl. 2, pp. S327-S339

[10] Lauriat, G., Desrayaud, G., Effect of surface radiation on conjugate natural convection in partially open enclosures, *Int. J. Therm. Sci*., 45 (2006), 4, pp. 335-346

[11] Wang, H., et. *al.*, Numerical Study of Natural Convection-Surface Radiation Coupling in Air-Filled Square Cavities, *C. R. Mecanique*, 334 (2006), 1, pp. 48-57

[12] Astanina, M., et .al, Effect of thermal radiation on natural convection in a square porous cavity filled with a fluid of temperature-dependent viscosity, *Therm. Sci.*, DOI: 10.2298/TSCI150722164A

[13] Hamimid, S., Guellal, M., Numerical analysis of combined natural convection-internal heat generation source-surface radiation, *Therm. Sci.*, 20 (2016), 6, pp. 1879-1889

[14] Hamimid, S., et. *al.*, Numerical Simulation of Combined Natural Convection Surface Radiation for Large Temperature Gradients, *J. Thermophys. Heat Transfer*, 29 (2015), 3, pp.1509-1517

[15] Bouafia, M., et. *al.*, Non-Boussinesq convection in a square cavity with surface thermal Radiation, *Int. J. Therm. Sci*., 96 (2015), pp.236-247

[16] Modest, M. F., *Radiative Heat Transfer*, 2nd ed., Academic Press, Sandi ego, CA, 2003