International Journal of Thermal Sciences 77 (2014) 38–46

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Gas radiation effects on opposing double-diffusive convection in a non-gray air–H_2O mixture

Siham Laouar-Meftah [a,*], Mohamed Cherifi [a], Denis Lemonnier [b], Abderrahmane Benbrik [a]

[a] Faculty of Hydrocarbon and Chemistry, M'hamed Bougara University, Boumerdes, Algeria
[b] Institut Pprime, CNRS, ENSMA, University of Poitiers, Futuroscope, Poitiers, France

ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form
7 August 2013
Accepted 10 October 2013
Available online 18 November 2013

Keywords:
Gas radiation
Square cavity
Double diffusion
SLW radiative model
Discrete ordinates

ABSTRACT

We studied numerically the effects of gas radiation on double-diffusive convection in a square enclosure filled with a non-gray air–H_2O mixture at different concentrations. Uniform temperatures and concentrations are imposed along the two vertical side walls of the enclosure so as to induce opposing thermal and mass buoyancy forces within the fluid. In this work, the radiative aspect of the problem is treated by the discrete ordinate method (to solve the radiative transfer equation) and the SLW spectral model (to account for the radiative properties of the non-gray mixture). Gas absorption varies with the local concentration of H_2O, which induces a strong direct coupling between the concentration and thermal fields that otherwise would not exist. Numerical results show that radiative effects on the characteristics of streamline, temperature and concentration fields are important, and depend on the nature of the flow regime (thermal at 5% H_2O, transitional at 10% and mass at 25%). The total heat transfer is reduced whatever the flow regime and the mass transfer is also affected, outside the thermal flow.

1. Introduction

In double-diffusive natural convection, the flow is induced by the simultaneous action of thermal and mass buoyancy forces. Earlier, this transport phenomenon was widely studied in different geometries by considering a transparent medium (no radiation). More recently, the problem of combined double diffusive convection with volumetric radiation attracted the attention of many scientists, owing to developments in several engineering applications and industrial processes (such as nuclear reactors, crystal growth, combustion chambers, and so on). Most of the studies dealing with this kind of coupling use the simple assumption of a medium with uniform absorption over space and wavelengths (gray and homogeneous medium) [1–4]. A limited number of them considered the more realistic situation of an absorption coefficient proportional to the local concentration of the absorbing species [5,6], but still under the gray gas assumption. To date, there are few investigations dealing with double diffusion–radiation in gaseous mixtures based on the real (non-gray) radiative properties of the medium (absorption varies with temperature, concentration and wavelength). In this context, we can mention the numerical studies by Meftah et al. [7,8] and Laouar-Meftah [9] who have analyzed the interaction of gas radiation and double diffusive natural convection in a non-gray participating mixture (air–CO_2 and air–H_2O). The authors used the SLW spectral model of Denison and Webb [10] with discrete ordinate method to account for the real radiative participation of the medium. They showed that, at steady state and in aiding cases (cooperating buoyancy forces), radiation creates oblique stratifications in temperature and concentration fields, decreases the Nusselt numbers and slightly reduces the Sherwood number. Recently Ibrahim and Lemonnier [11] have considered the same problem in N_2–CO_2 mixture at transient state. The results show that radiation accelerates the convergence to steady state in aiding case, while it favors the generation of instabilities and delays the arrival to a stable solution in opposing one. In this paper, we investigated the effects of gas radiation on double-diffusive convection in air–H_2O mixture at steady state and in opposing case, when temperature and concentration gradient are set as to induce buoyancy forces in opposing directions. This configuration may yield complex flow structures, where the balance of thermal to mass forces may be significantly modified by radiative absorption within the fluid. In this paper, the average concentrations of pollutant considered correspond to mole fractions: 5%, 10% and 25% H_2O.They basically correspond (for a transparent fluid) to thermally dominated flow, transitional flow and mass dominated flow.

* Corresponding author. Fax: +213 24 819172.
E-mail address: laouarmeftah@gmail.com (S. Laouar-Meftah).

1290-0729/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.10.004

Nomenclature

a	weighting coefficient in the SLW model
C	species concentration, mol/m^3
D	binary mass diffusion coefficient, m^2/s
I	radiation intensity, W/m^2 × sr or W/m^2 × sr × μm
N	buoyancy ratio
N_g	number of gray gas
Nu	Nusselt number
q^{inc}	incident heat flux at wall, W/m^2
q_R	radiative flux, W/m^2
s	direction of radiation propagation
Sh	Sherwood number
S_R	radiative source term, W/m^3
u,v	horizontal and vertical velocities, m/s
w	weight of angular quadrature
x_H	molar fraction of H_2O at hot wall
x_L	molar fraction of H_2O at cold wall
x_{H_2O}	average molar fraction of H_2O at reference conditions = $(x_H + x_L)/2$
α	mixture thermal diffusivity, m^2/s
ε	emissivity of the wall
κ	absorption coefficient, 1/m
μ,η	direction cosines
γ	mixture kinematic viscosity, m^2/s
σ	Stefan–Boltzmann constant, W/m^2 × K^4
ω	vorticity, 1/s
ψ	stream function, m^2/s

Subscript

C	cold
c	convective
H	hot or high
k	kth gray gas
L	low
m	mth direction of radiation propagation
R	radiative quantity
x,y	in the x- or y-direction
0	reference quantity

2. Analysis and modeling

2.1. Physical model and assumptions

We consider a square cavity of width L (Fig. 1), whose horizontal walls are completely reflective, perfectly insulated and impermeable to mass transfer while the two vertical walls are black and maintained at two different temperatures ($T_H > T_C$) and concentrations ($C_L < C_H$), respectively. The cavity is filled with a mixture of pure air (considered as perfectly transparent) and H_2O vapor (an absorbing, emitting and non-scattering species) acting as a pollutant. This fluid is assumed Newtonian, incompressible, with constant thermophysical properties and satisfying the Boussinesq approximation. The flow is two-dimensional, stationary and laminar.

Note that in the most severe conditions investigated here (25% H_2O), the mixture density varies from 0.53 kg/m^3 at the cold wall (lower temperature, highest concentration of H_2O) to 0.60 kg/m^3 at the hot wall (highest temperature, null concentration of H_2O). Consequently, the global density variations within the fluid do not exceed 12% if related to the reference value of 0.57 kg/m^3 (calculated at the average temperature and concentration). Therefore, the Boussinesq approximation can reasonably be considered as valid in all the cases considered in this study. Another criterion yields the same conclusion. It is based on the factors ε_T and ε_C defined by Sun and Lauriat [12] to characterize the thermal and solutal deviations from the Boussinesq approximation: according to our data, these factors are respectively equal to 0.3 and 0.1 (in the most severe case) and are in the range where the authors conclude that the approximation holds.

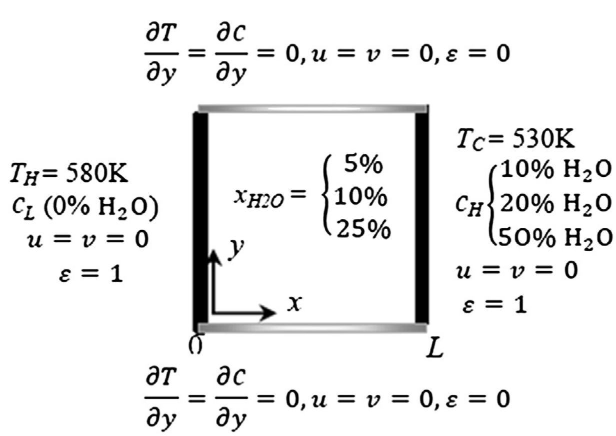

Fig. 1. Physical model.

2.2. Governing equations

The fluid motion is described by the following set of equations, expressed in the vorticity (ω)–stream function (ψ):

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \gamma\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2}\right) + g\left(\beta_T\frac{\partial T}{\partial x} + \beta_C\frac{\partial C}{\partial x}\right) \tag{1}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + S_R \tag{2}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) \tag{3}$$

$$-\omega = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} \tag{4}$$

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x} \tag{5}$$

where β_T and β_C are the thermal and mass expansion coefficients, respectively defined by:

$$\beta_T = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_{p,c} = \frac{1}{T_0} \tag{6}$$

$$\beta_C = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial c}\right)_{p,T} = \frac{M_{air} - M_{H_2O}}{\rho_0} \tag{7}$$

M_{air} and M_{H_2O} are, respectively, the molecular mass of air and H_2O.

In the energy Equation (2), S_R stands for the radiation source field. It is calculated as follows.