Journal of Quantitative Spectroscopy & Radiative Transfer 113 (2012) 1689–1704

Contents lists available at SciVerse ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Numerical prediction of heat transfer by natural convection and radiation in an enclosure filled with an isotropic scattering medium

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ARTICLE INFO

Article history:
Received 7 January 2012
Received in revised form
14 April 2012
Accepted 20 April 2012
Available online 27 April 2012

Keywords:
Numerical analysis
Heat transfer
Natural convection
Volumetric radiation
Thermal lattice Boltzmann method
Discrete ordinates method

ABSTRACT

This paper deals with the numerical solution for natural convection and volumetric radiation in an isotropic scattering medium within a heated square cavity using a hybrid thermal lattice Boltzmann method (HTLBM). The multiple relaxation time lattice Boltzmann method (MRT-LBM) has been coupled to the finite difference method (FDM) to solve momentum and energy equations, while the discrete ordinates method (DOM) has been adopted to solve the radiative transfer equation (RTE) using the S8 quadrature. Based on these approaches, the effects of various influencing parameters such as the Rayleigh number (Ra), the wall emissivity (ε_i), the Planck number (Pl), and the scattering albedo (ω), have been considered. The results presented in terms of isotherms, streamlines and averaged Nusselt number, show that in absence of radiation, the temperature and the flow fields are centro-symmetrics and the cavity core is thermally stratified. However, radiation causes an overall increase in the temperature and velocity gradients along both thermally active walls. The maximum heat transfer rate is obtained when the surfaces of the enclosure walls are regarded as blackbodies. It is also seen that the scattering medium can generate a multicellular flow.

1. Introduction

The problem of natural convection in presence of volumetric radiation remains an interesting topic for the research community due to its various applications in industrial processes, such as cooling of electronic devices, thermal insulation, roof ventilation, heat buildings, solar capture, and heat exchangers, etc.

The volumetric radiation of semi-transparent medium (the component scatters, absorbs and emits thermal radiation) coupled to the natural convection has a direct influence on the thermal field through the disparities in absorption and emission phenomena. However, the variation of the dynamic field is indirectly influenced by the radiative effects. It is interesting to note that a detailed parametrical study focusing on the characterizing parameters in combined convection and radiation was rarely addressed in details. Indeed the effects on the flow and heat transfer of parameters as Rayleigh number, Planck number, wall emissivity, and the scattering albedo are present for wide ranges in several situations in industry and derive from a real engineering applications such as furnaces, drying process, sterilization, heat treatment, double glazing in building, microwave oven, microelectronics petrochemical industry, heat exchangers, cooling electronic devices, etc. Hence we made the choice to perform some numerical experiences which are linked to practical cases.

Various conventional Computational Fluid Dynamics (CFD) methods such as finite difference method (FDM),

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http://dx.doi.org/10.1016/j.jqsrt.2012.04.017

Nomenclature

$\vec{g}$	gravitational acceleration, ms^{-2}
I	radiation intensity, $W\,m^{-2}\,sr^{-1}$
i_0	black body radiation intensity, $W\,m^{-2}\,sr^{-1}$
I	dimensionless radiation intensity,$=i/4\sigma T_0^4$
K	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	enclosure width, m
M	number of discrete directions
$\vec{n}$	outer unit vector normal
Nu_c	average convective Nusselt number
Nu_R	average radiative Nusselt number
Nu_T	average total Nusselt number at the side walls
Pl	Planck number,$=(k/L)/(4\sigma T_0^3)$
Pr	Prandtl number,$=\nu/\alpha$
q_R	radiative heat flux, $W\,m^{-2}$
Q_R	dimensionless radiative heat flux,$=q_R/4\sigma T_0^4$
Ra	Rayleigh number,$=g\beta(T_h-T_c)L^3/\nu\alpha$
R	arbitrary lattice point
T	temperature, K
T_h, T_c	hot and cold wall temperatures, K
T_0	average temperature,$=(T_h+T_c)/2$, K
u, v	velocity components, ms^{-1}
U, V	dimensionless velocity components, $(U=uL/\alpha$, $V=vL/\alpha)$
w_m	quadrature weights
x, y	cartesian coordinates, m
X, Y	dimensionless coordinates, $(X=x/L$, $Y=y/L)$

Greek symbols

α	thermal diffusivity, m^2s^{-1}
β	volumetric expansion coefficient, K^{-1}
δ_t	time step
$\vec{\nabla}$	dimensionless gradient operator, $=\partial/\partial X.\vec{i}+\partial/\partial Y.\vec{j}$
ε	emissivity of radiative wall
κ	absorption coefficient, m^{-1}
μ, ξ	direction cosines
ν	kinematic viscosity, $m^2\,s^{-1}$
ς	dimensionless relaxation time
ω	scattering albedo
$\vec{\Omega}$	direction vector, $=\mu\vec{i}+\xi\vec{j}$
ψ	stream function, m^2s
Ψ	dimensionless stream function
ρ	density, kgm^{-3}
σ	Stefan-Boltzmann constant, $W\,K^{-4}\,m^{-2}$
τ	optical thickness
θ	dimensionless temperature, $=(T-T_0)/(T_h-T_c)$
Θ_0	reference temperature ratio, $=T_0/(T_h-T_c)$

Subscripts

C	cell center
c, h	cold, hot
f	Fluid
M	index for finite number of direction in DOM
R	radiative quantity
S	Solid
T	total conductive and radiative quantity
W	Wall
0	reference state
1, 2, 3, 4	left wall, right wall, low wall, high wall
E, W, S, N	east, west, south, north

Superscripts

+	post-collision

finite element method (FEM) and finite volume method (FVM) were used to address the coupled convection and volumetric radiation by solving the energy equation. In previous bibliographic references, various numerical methods are traditionally used to solve the radiative part of the problem, among these include the P-1 approximation [1–3], the zonal method [4–6], the flux method [4–6], the ray-tracing method [7,8], the Monte Carlo method [7,8], the exchange factors method [9,10], the integration product method (IPM) [11], the finite volume method (FVM) [11–14], the discrete transfer method (DTM) [15–17] and the discrete ordinates method (DOM) [18–24], for instance.

Initial works on the interaction of volumetric radiation and natural convection began in the 80s by Viskanta [7], Yang [25] and Menguc and Viskanta [8]. In these studies, the medium was considered as a gray gas (radiative properties of absorption and emission are independent of the wavelength and temperature). Among the interesting investigations in this area, one can refers to the work of Lauriat [1], who examined this phenomenon for a two-dimensional vertical cavity at different optical thickness, whereas the radiative part of the problem has been treated by the method of spherical harmonics P1. It was shown for the last work, that radiation increases the overall heat transfer in the cavity. Desrayaud and Lauriat [26] later extended the study of a fluid layer of the vertical wall. Fusegi and Farouk [3] quantitatively studied the interaction of convection and radiation of a gray gas in square cavity asymmetrically heated using the P1 approach. In other side, the natural convection induced by the irradiation of the fluid layer have been studied by Webb and Viskanta [27].

Yucel et al. [22] used the DOM for calculating the radiative source term to address the same problem studied by the Ref. [27]. They stipulated that the volumetric radiation changes the distribution of temperature, heating the core of the cavity and creating multicellular structures in flow when the optical thickness of the medium or diffuse radiation fluid is low. The authors conclude that the method P1 can be a source of error in comparison with the DOM for the evaluation of parietal fluxes. These same authors [23] later studied the changes in the buoyant flow patterns and temperature distributions due to the presence of radiation in inclined or heat generating enclosures. In the same