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Analysis of non-Fourier conduction and volumetric radiation in a concentric spherical shell using lattice Boltzmann method and finite volume method

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ABSTRACT

Application of the lattice Boltzmann method (LBM) has been extended to formulate and solve the energy equation of a non-Fourier conduction and radiation heat transfer problem in a concentric spherical shell. The enclosed conducting-radiating medium is absorbing, emitting and scattering. The non-Fourier conduction effect is induced by thermally perturbing one of the boundaries and incorporating the finite propagation speed of the thermal wave front in Fourier's law of heat conduction. The volumetric radiative information needed in the energy equation has been computed using the finite volume method (FVM). To establish the accuracy of the LBM approach, with volumetric radiative information obtained from the FVM, the energy equation is also solved using the FVM. Effects of extinction coefficient, scattering albedo, conduction–radiation parameter, emissivity, radius ratio and the magnitude of thermal perturbations are studied on transient temperature distributions. Effects of the aforesaid parameters on the steady-state conduction, radiation and total energy flow rates are also studied. Steady-state LBM and FVM results are compared. In all the cases, the LBM results compare exceedingly well with the FVM results, and LBM has a faster convergence than the FVM.

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1. Introduction

Analysis of combined mode conduction and radiation heat transfer is important in many thermal systems. Its consideration is paramount in the analysis and design of boilers, furnaces and insulations [1–4]. Its accounting is equally important for the correct analysis of phase change processes of semi-transparent materials such as glass and silicon [5,6]. Radiation and conduction are important modes of heat transfer in burners based on porous medium combustion [7,8]. Combined mode conduction and radiation also finds application in laser based manufacturing process [9,10] and in the area of bioheat transfer pertaining to laser surgery and ablation of malignant tissues [11–13]. Consideration of thermal radiation with and without conduction in a spherical enclosure containing an absorbing, emitting, and scattering medium finds applications in the analysis of nuclear reactors, spherical propulsion systems, astrophysics, droplet combustion, droplet radiator systems for spacecraft thermal control, etc. [14,15].

Combined mode conduction and/or radiation problems in a spherical shell have been analyzed by many [15–21]. In any geometry, thermal response of the system in transient state is quite different with and without consideration of finite propagation speed of the conduction wave front [21–34]. Conduction heat transfer as per Fourier's law does not consider any time lag between the cause (thermal perturbation) and the effect (manifestation of energy flow rate). In other words, as per Fourier's law of heat conduction, the effect of the thermal perturbation is instantaneously felt throughout the medium. In reality, however, it is never so. Thermal wave front does take some finite time to move from one location to the other. Examples are plenty [21–34]. In any system, if the next pulse of thermal perturbation is imposed before the effects of the previous ones have died out, consideration of finite propagation speed becomes important. Further, even when any region of the system is thermally perturbed, like suddenly changing the temperature of any boundaries or changing imposed heat flux, if the temporal change is looked at time scale lower than the system time scale $\frac{L\ (\mathrm{m})}{C\ (\mathrm{m\ s^{-1}})}$ where L is the characteristic length and C is the propagation speed of the thermal wave front, consideration of finite propagation speed becomes essential. The modified form of the heat conduction equation that accounts for the finite propagation speed of the conduction wave front is known as non-Fourier conduction.

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Nomenclature

a_i	weight in LBM formulation
b_i	weight in LBM formulation
C	speed of thermal wave, (m s^{-1})
D^m	directional weight in direction m
e_i	non-dimensional propagation velocity in the direction i in the lattice
$\vec{e}_r$	unit radial vector
f_i	non-dimensional particle distribution function in the i direction
$f_i^{(0)}$	non-dimensional equilibrium particle distribution function in the i direction
G	incident radiation (W m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
N	conduction–radiation parameter
N_θ	number of divisions of the polar space
q_C	non-dimensional heat flux
q_T	non-dimensional total heat flux
r_1	non-dimensional radius of the inner sphere
r_2	non-dimensional radius of the outer sphere
r_i	non-dimensional radial position of the ith node

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	extinction coefficient (m^{-1})
ε	emissivity
θ	polar angle
ϕ	azimuthal angle
κ	absorption coefficient (m^{-1})
ν	expansion parameter
Θ	normalized temperature, $\frac{T-T_2}{T_1-T_2}$
κ_a	absorption coefficient (m^{-1})
Γ	thermal relaxation time (s)
ω	scattering albedo
σ_s	scattering coefficient (m^{-1})
η	normalized radial distance, $\frac{r-r_1}{r_2-r_1}$
μ	direction cosines
ζ	non-dimensional time
Ω	solid angle (sr)
$\Delta\Omega$	elemental solid angle (sr)
Ψ	non-dimensional energy flow rate

Superscript

m	indices for discrete polar angles

Subscripts

1, 2	inner and outer spherical walls
C	conductive
w	wall
R	radiative
ref	reference
T	total

Realizing its importance and applications, many researchers have studied combined conduction and/or radiation heat transfer with non-Fourier effect. In the presence of volumetric radiation, owing to the angular dependence of radiation that leads to integro-differential radiative transfer equation, the formulation and solution become very much involved. Though many researchers have investigated non-Fourier heat conduction alone [21,26,28,31,33], some have done the analyses in the presence of volumetric radiation [22–25,27,29,32]. Different numerical radiative transfer methods like the P-N approximation [22], discrete ordinate method (DOM) [12,34], the finite volume method (FVM) [24,25,27,29,32], etc., have been used to compute the radiative information needed in the energy equation which too has been solved using different methods like the Green's function method [21] the finite difference method (FDM) [22] and the FVM [27,29].

During the past two decades, a wide range of problems in science and engineering have been analyzed using the lattice Boltzmann method (LBM) [35–37]. LBM has found extensive usage in the study of fluid flow and thermal problems [35–37]. In the recent past, Mishra and co-workers and others have used LBM to analyze many heat transfer problems involving thermal radiation [38–45]. Recently Chaabane et al. [43–45] have used the LBM to formulate and solve the energy equations of combined mode conduction and radiation heat transfer problems in 2-D cylindrical enclosure [43] and 2-D rectangular enclosure [44,45]. Heat transfer by conduction was assumed to follow Fourier's law. In their work, they used control volume finite element method to compute the divergence of radiative heat flux needed in the LBM formulation. The usage of the LBM to formulate and solve the energy equations of different kinds of combined mode problems in various geometries by all authors was successful, and the experience was encouraging.

Mishra and co-workers have also used LBM to solve non-Fourier conduction and radiation heat transfer in a planar [24,25] and cylindrical geometry [32]. Without radiation, Mishra and Sahai [31] have recently extended application of the LBM to non-Fourier heat conduction in a cylindrical and spherical geometry. However, as far as application of the LBM to analyze heat transfer with non-Fourier conduction and radiation in a spherical shell is concerned, no work has been reported so far. The present work, therefore, aims at extending the usage of the LBM to formulate and solve the energy equation of a combined mode non-Fourier conduction and radiation in a concentric spherical shell.

In the present work, the energy equation of a combined mode non-Fourier conduction and radiation in a concentric spherical shell containing radiating and conducting medium is formulated and solved using the LBM. The volumetric radiative information needed in the solution of the energy equation is computed using the FVM. Effects of operating and geometric parameters like the extinction coefficient, the scattering albedo, the conduction–radiation parameter, the boundary emissivity, the radius ratio and the magnitudes of the thermal perturbations of the boundaries on normalized radial temperature distributions at different instants including the steady-state (SS) are analyzed. At the SS, for all the parameters, radial distributions of conductive, radiative and total energy flow rates are also studied. For the same number of control volumes and rays, in all cases, distributions of SS temperature and energy flow rate obtained using the LBM are compared against those obtained using the FVM. The number of iterations for the SS results in LBM and FVM are provided.

In the following sections, first the energy equation of problem is formulated in the LBM approach. LBM approach being termed as a mesoscopic, concurrently, the governing equation in the macroscopic (continuum) approach is provided. Using Chapman–Enskog multi-scale expansion, the consistency of the LBM equation is proved. Expression for calculation of volumetric radiative information needed in the energy equation is provided and its solution using the FVM is briefly discussed. In the next section on results and discussion, effects of various parameters on temperature and energy flow rate distributions are analyzed. Conclusions are made at the end.

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