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Analysis of conduction–radiation heat transfer during phase change process of semitransparent materials using lattice Boltzmann method

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ABSTRACT

This article deals with the analysis of solidification of a 2-D semitransparent material using the lattice Boltzmann method (LBM). Both conduction and radiation terms in governing energy equation were computed using the LBM. First, the LBM formulation regarding conduction component was validated and the results analyzed. Next, the results involving phase change or radiation term in the LBM were compared with the finite volume method (FVM). The results show good accuracy and less time consumption during LBM implementation. Finally, temperature distribution, the location of solid-liquid front, mushy zone thickness and the effects of heat transfer parameters were studied.

1. Introduction

Heat transfer problems with phase change, which is called Stefan problem, have many applications in many areas such as casting, freezing, evaporations, welding, crystallization, weather forecasting and solidification or melting of metals and semitransparent materials such as glasses, fluorides and ceramics [1–7]. The main purpose of this paper is studying the phase change of semitransparent materials which is strongly influenced by volumetric radiation. Also, in these problems the most time consuming part is computation of volumetric radiation. So finding the ways to calculate the volumetric radiation more quickly is inevitable.

The solidification problems in semi-transparent materials include phase change and radiative heat transfer, so these problems lead to nonlinear set of equations at the moving front and are too complicated. Then, analytical solutions are limited to simple cases and so difficult to achieve [8]. Nowadays, computational methods have appeared as effective techniques to analyze the phase change process. The finite difference method (FDM) and finite element method (FEM) were used to solve fluid dynamics and heat transfer problems from about 60 years ago [9–11]. In 1980, the FVM, which belongs to the same family of weighted residual method, was developed to solve heat and mass transport phenomena [12]. Another useful method was the LBM which was introduced by McNamara and Zanetti in 1988. This new powerful method is applied widely in engineering problems especially when we encounter complex phenomena and geometries [13–18]. Unlike the typical computational fluid dynamics methods that are based on continuum mechanics, LBM originate from mesoscopic kinetic equation and statistical physics approach. Bridging the gap between continuum mechanics and molecular dynamics is the main idea of Boltzmann. In the LBM, we discretize lattice Boltzmann equation through time and space and at each lattice node, a set of distribution functions are stored. These distribution functions move along specified directions to the neighboring nodes. The number of directions depends on the lattice arrangement. Because of the complication of collision term, it is difficult to solve Boltzmann equation. Bhatnagar et al. [28] introduced

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Nomenclature

A	length (m)
B	width (m)
b	number of directions in lattice
C	heat capacity (kJ/m^3 K)
c_p	specific heat (kJ/kg K)
e_i	the propagation speed in the lattice in i direction (m/s)
$\vec{e}_i$	the propagation velocity in the lattice in i direction (m/s)
f_l	phase fraction volume of the liquid phase
G	incident radiation (W/m^2)
H	total enthalpy (kJ/kg)
I	intensity (W/m^2)
k	thermal conductivity (W/mK)
L	latent heat (kJ/kg)
M	total number of intensities
N	conduction–radiation parameter$=k\beta/4\sigma T_s^3$
n_i	the i direction particle distribution function (K)
$n_i^{(0)}$	the i direction equilibrium distribution function (K)
q_R	radiative heat flux (W/m^2)
$\vec{r}$	lattice node
St	Stefan number$=C_p\Delta T/L$
T	temperature (K)
t	time (s)
w_i	the i direction weight factor in a lattice
x,y	coordinate directions

Greek symbols

α	thermal diffusivity (m^2/s)
β	extinction coefficient (m^{-1})
κ	absorption coefficient (m^{-1})
ε	emissivity
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant$=5.67\times10^{-8}$ (W/m^2 K^4)
σ_s	scattering coefficient (m^{-1})
τ	relaxation time (s)
ω	scattering albedo
Φ	source term (K/s)

Subscripts

b	black
i	lattice direction index
0	initial
l	liquid phase
m	melting
s	solid phase
w	wall

Superscripts

(eq)	equilibrium
m	direction

a simplified model for collision operator without introducing significant error to the outcome of the solution. In this article we use (Bhatnagar, Gross and Krook) BGK approximation.

Thermal radiation appears just in the boundary conditions during phase change of metals. But we face with different pattern in semitransparent materials. Thermal radiation penetrates inside the medium of these materials and consideration of volumetric radiation is inevitable.

Difference methods such as FVM, FEM, FDM, discrete transfer method (DTM), and discrete ordinate method have been used to study the radiation and conduction heat transfer [19–25]. Chan et al. [19] introduced a phase change model with internal radiation heat transfer. The LBM solution for the 2-D energy equation of conduction–radiation problem has been done by Mishra et al. [22]. Collapsed dimension method (CDM) was used to compute the radiative information in their study. Chatterjee and Chakraborty [24] used an enthalpy-source based lattice Boltzmann model for conduction dominated phase change problem. Raj et al. [26] studied the 1-D solidification problem of semitransparent material using the LBM. The DTM was used to compute the radiative information in their study. Mishra et al. [27] study the solidification of a 2-D semitransparent medium using the LBM. The FVM was used to compute the radiative information in their study.

As it mentioned before, several researchers have extended the application of the LBM to formulate and solve energy equations of heat transfer problems involving thermal radiation. In all the previous studies, the volumetric thermal radiation was always computed using the conventional numerical radiative transfer methods such as the DOM, the DTM, the CDM, and the FVM; so in none of the previous studies, the computation of radiative information, which is the main time consuming component, has been computed using the LBM.

In all solidification problems which mentioned before, the computational grids of the conventional radiation solvers such as the DTM, the DOM, the FVM, etc., have always been different from the lattices of the LBM. Thus, the radiative information computed using these methods required to be interpolated to the lattice nodes that required an additional computational step. Therefore the LBM implementation to compute both the energy and the radiative equations leads to less time consumption.

Recently, Asinari and co-workers [29] investigated The LBM usage to compute radiative information in a participating medium. The aim of this article is using the LBM to compute both conduction and radiation components of energy equation during phase change of semitransparent materials.

2. Formulation

Consider a rectangular plate of semitransparent material with length A and width B with initial temperature of T_0 which is higher than its melting temperature (T_m)