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GPU accelerated numerical study of PCM melting process in an enclosure with internal fins using lattice Boltzmann method

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ABSTRACT

Latent heat thermal energy storage (LHTES) has many applications in engineering fields such as electronic cooling, thermal storage of solar energy, heating and cooling in buildings, waste heat utilization and so on. The advantages of LHTES over sensible thermal energy storage or chemical energy storage techniques are high energy density and phase change at nearly constant temperature. Unfortunately, the low thermal conductivity of PCMs increases the thermal gradient in the energy storage system and impedes the heat transfer efficiency. However, high thermal conductivity fins could be used to promote the melting process in PCM enclosures. As a powerful numerical method developed during the past two decades, lattice Boltzmann method (LBM) was used to simulate the conjugate heat transfer in the solid walls, fins and PCM region. By changing the velocity field and diffusivities, only one distribution function was needed to simulate the melting with natural convection in PCMs and conduction in fins and enclosure surfaces. As a result, the thermal boundary conditions on the interfaces of PCMs, fins and solid walls were satisfied automatically. By using enthalpy-based multiple-relaxation-time (MRT) LBM model, the iteration steps for the latent-heat source term were avoided. Under this case, the conjugate convective heat transfer with phase change is modeled efficiently. The graphics processing units (GPU) computing becomes attractive since the advent of CUDA which includes both hardware and programming environment in 2007. Consequently, the developed MRT LBM code is further implemented to run on GPU. High computation speed was achieved. The melting process in PCMs was investigated for different materials of fins and walls, number of fins, fin configurations, hot wall temperature, thermal boundary conditions, and inclination angle of the PCM cavity. Lattice Boltzmann method implemented on GPU was demonstrated as an efficient approach to study the PCM melting process with internal fins.

1. Introduction

Latent heat thermal energy storage is the most efficient approach to store the thermal energy [1–6]. LHTES has the characteristic of higher energy storage density and isothermal nature of phase change compared with sensible thermal energy storage and chemical energy storage. However, it is well known that the major drawback for latent heat thermal energy storage is the low thermal conductivity of PCMs. Under this circumstance, the technologies of enhancing heat transfer efficiency of PCMs attracted lots of attention during the past decades. The techniques for improving the heat transfer in LHTES could be categorized as the follows: (1) use of extended internal fins [7–13], (2) use high thermal conductivity porous matrices in PCMs [14–16], (3) add high thermal conductivity nanoparticles in PCMs [17–19], (4) micro-encapsulated PCMs [20,21]. The current numerical study focuses on the enhancement of PCM melting process in a thick-wall cavity by using internal fins. Sharifi et al. studied the conjugate heat transfer in the cavity walls, fins and the molten PCM by finite volume approach [7]. They also derived analytical correlations to quickly estimate melting rates. Lacroix and Benmadda investigated the solidification of a phase change material from a finned vertical wall using a fix-grid enthalpy approach [8]. They found that it is more efficient to use a few long fins than several short fins for promoting the melting process. Akhilesh et al. studied the rectangular PCM composite with vertical fins heated from above by only considering the conduction [10]. They presented that there is a critical value for the number of fins beyond which the melting efficiency is not improved by adding more internal fins. Lamberg and Siren derived a simplified analytical model to predict the solid–liquid interface location and temperature distribution of the fins during solidification process in PCM storage [12]. Levin et al. optimized the design of latent heat thermal

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Nomenclature

A	PCM cavity area
c	lattice speed
c_s	sound speed
C_p	specific heat
C_{pe}	effective specific heat in simulation
C_{pf}	PCM specific heat
$C_{p,ref}$	reference specific heat
C_{pw}	fins and walls specific heat
$\boldsymbol{e}_i$	discrete lattice velocity in direction i
Fo	Fourier number $Fo = \frac{\alpha_f t}{L^2}$
Fo_f	Fourier number at which PCM cavity is fully melted
F_i	discrete body force in direction i
$\boldsymbol{f}$	body force per unit volume
f_l	liquid fraction
f_{lt}	total liquid fraction
f_i	density distribution function in direction i
f_i^{eq}	equilibrium distribution function of density in direction i
$\boldsymbol{g}$	gravitational acceleration
g	gravitational acceleration in vertical direction
g_i	temperature distribution in direction i
g_i^{eq}	equilibrium distribution function of temperature in direction i
H	enthalpy
H_r	reference enthalpy
H_s	total enthalpy corresponding to the solidus temperature
H_l	total enthalpy corresponding to the liquidus temperature
h_{sl}	latent heat of melt
k_{pcm}	thermal conductivity ratio in PCM region
k_{pw}	thermal conductivity ratio between fins and liquid PCM
k_{cp}	ratio defined as $k_{cp} = \frac{\rho_f C_{pf}}{\rho_w C_{pw}}$
L	PCM square cavity height
$L2$	L2 error
$\boldsymbol{M}$	transformation matrix
$\boldsymbol{m}$	distribution function of temperature in momentum space
$\boldsymbol{m}^{eq}$	equilibrium distribution function of temperature in momentum space
N	number of internal fins
NG	number of grids in x direction for conjugate heat transfer test
Nu_{ave}	average Nusselt number $Nu_{ave} = -\int_0^1 \frac{\partial\theta}{\partial x^*} dy^*$
Pr	Prandtl number $Pr = \frac{\upsilon_f}{\alpha_f}$
p	pressure
p^*	dimensionless pressure
Ra	Rayleigh number $Ra = \frac{g\beta(T_h - T_m)L^3}{\alpha_f \upsilon_f}$
T	temperature
T_h	hot wall temperature
T_m	melting temperature of PCM
$\boldsymbol{S}$	the relaxation matrix in momentum space
Ste	Stefan number $Ste = \frac{C_{pf}(T_h - T_m)}{h_{sl}}$
s_0	element of the relaxation matrix $\boldsymbol{S}$
s_e	element of the relaxation matrix $\boldsymbol{S}$
s_ε	element of the relaxation matrix $\boldsymbol{S}$
s_j	element of the relaxation matrix $\boldsymbol{S}$
s_q	element of the relaxation matrix $\boldsymbol{S}$
t	time
t^*	dimensionless time
t_d	distance between fins
t_d^*	dimensionless distance between fins
t_f	fin length
t_f^*	dimensionless fin length
t_s	fin thickness
t_s^*	dimensionless fin thickness
t_w	wall thickness
t_w^*	dimensionless wall thickness
$\boldsymbol{u}$	velocity
u	velocity in horizontal direction
u^*	dimensionless velocity in horizontal direction
v	velocity in vertical direction
v^*	dimensionless velocity in vertical direction
$\boldsymbol{x}$	vector of location
x	horizontal coordinate
x^*	dimensionless horizontal coordinate
y	vertical coordinate
y^*	dimensionless vertical coordina

Greek symbols

α_f	liquid state PCM thermal diffusivity
α_{pcm}	PCM thermal diffusivity
α_w	fins and walls thermal diffusivity
β	thermal expansion coefficient
λ	thermal conductivity
λ_f	liquid state PCM thermal conductivity
λ_{ice}	thermal conductivity of ice
λ_{liquid}	thermal conductivity of liquid water
λ_{pcm}	PCM thermal conductivity
λ_s	solid state PCM thermal conductivity
λ_w	fins and walls thermal conductivity
ϕ	variable in advection diffusion equation
γ	inclination angle between the bottom of PCM cavity and positive x direction
μ	fluid dynamic viscosity
υ_f	fluid kinematic viscosity
θ	dimensionless temperature
ρ	density
ρ_f	PCM density
ρ_w	fins and walls density
τ_f	dimensionless relaxation time of density
τ_s	dimensionless relaxation time of temperature
ω_i	weight coefficient in direction i
t	time step
$\boldsymbol{\Lambda}$	relaxation matrix in velocity space
$\boldsymbol{\Lambda}_{ik}$	relaxation matrix in velocity space

management system with internal fins for cooling an electronic device [13]. The aim of their study was to minimize the height of PCM system while the capability of absorbing heat released from electronic devices was kept. Their results showed that the optimal PCM percentages depend on number and length of fins as well as thermal conditions.

Lattice Boltzmann method (LBM) has been developed as a powerful numerical method for complex heat transfer and fluid dynamics problems during the past two decades [22,23]. As a mesoscopic method, lattice Boltzmann method has some advantages such as capability to capture detail information of fluid flow, parallel nature, and easy treatment of boundary conditions. The existing lattice Boltzmann approaches for solid–liquid phase change problems can be generally classified into three methods: (1) the phase-field method [24,25], (2) the enthalpy-based method [26–32], (3) the immersed boundary method [33]. For the phase-field method, the solid–liquid interface is implicitly tracked by an auxiliary parameter which varies smoothly across the diffusive