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Investigation of phase change material based battery thermal management at cold temperature using lattice Boltzmann method

Yutao Huo, Zhonghao Rao *

School of Electric Power Engineering, China University of Mining and Technology, Xuzhou 221116, China

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ABSTRACT

The power and energy densities of battery will decrease at cold temperature and the heat preservation is necessary to keep the working temperature. In this paper, the lattice Boltzmann model for phase change material based battery thermal management cold temperature is constructed and the effects of thermal conductivity, latent heat and environmental temperature have been considered. The results show that with the latent heat of phase change material (PCM), the temperature of battery decreases slowly and the temperature distribution can be guaranteed. However, once the PCM adjacent to the interface of battery and PCM, the temperature of battery drops faster and the temperature standard deviation rises sharply. Besides, the lower thermal conductivity, greater latent heat and higher environmental temperature are able to slow down the solidification process of PCM and keeps the temperature of battery. However, with larger latent heat of PCM, the battery temperature distribution gets more non-uniform, which is able to decrease the cycle life of battery.

1. Introduction

The battery thermal management (BTM) is of significant importance to power battery, especially for lithium-ion battery [1]. In recent years, most of the research only focused on the performance of BTM's heat dissipation at the excessive ambient temperature, since the thermal runaway will occur under extreme condition [2]. However, when the ambient temperature is low, the energy density and power densities of battery decrease sharply [3]. Consequently, the demand of temperature maintaining in low-temperature environment must be reached for BTM.

The thermal performance of BTM in low-temperature environment is divided into two parts, the heat preservation and heating. Heating is an effective way to keep the temperature of battery. The simplest way of battery warming is using high-temperature air or other liquid medium to transfer heat to battery [4]. Zhang et al. [4] used warm air (obtained from cabin) to heat the battery. However, the results showed that the heating method would increase the load of air-conditioning system. Another heating method is the electrical heating, using the ohmic heat or the Peltier effect [5,6]. Stuart and Hande [6] designed an alternating current (AC) internally heating for hybrid electrical vehicle (HEV) at cold temperature. The results showed that the heating process was accelerated when the amplitudes of AC was larger. Using the Peltier effect, Troxler et al. [5] have proposed a BTM using Peltier element to capture temperature difference of battery. The temperature controlling system was able to be used to warm battery. However, the efficiency of all the heating methods is not great enough at the extreme environment condition. Consequently, the heat preservation of BTM is essential as well.

The phase change material (PCM) has received more and more attention in temperature maintaining. During the phase change process, the temperature of PCM varies a little since a large amount of energy is consumed by latent heat. PCM has been successfully applied to cool down battery [7–9] in recent years. In the same way, the PCM is able to be used in heat preservation for battery.

The mass, momentum and heat transfer behaviors at solid-liquid interface are extremely complex, with which the analytical results are difficult to be obtained. Consequently, several numerical methods have been proposed to solve the solid-liquid phase change problem, including the computational fluid dynamics (CFD) method [10], dissipative particle dynamics (DPD) method [11,12] and molecular dynamics (MD) method [13]. Unlike the conventional CFD method, lattice Boltzmann (LB) is one of the methods derived from Boltzmann transport equation [14]. The LB method is simpler than conventional CFD method in programming. Besides, with the easy boundary treatment and inherently parallelizable computation, the LB method has been used to solve the solid-liquid phase change problem successfully [15]. Jiaung et al.

* Corresponding author.
E-mail address: raozhonghao@cumt.edu.cn (Z. Rao).

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Nomenclature

B	weighting function
c	lattice speed [m·s^{-1}]
c_s	lattice sound speed [m·s^{-1}]
C_p	specific heat at constant pressure [kJ·kg^{-1}·K^{-1}]
$\boldsymbol{e}_i$	discrete velocity in direction i [m·s^{-1}]
$\boldsymbol{F}$	force [N]
F_i	discrete force in direction i [N]
f_i	distribution function for density in direction i [kg·m^{-3}]
f_i^{eq}	equilibrium distribution function for density in direction i [kg·m^{-3}]
F_i	discrete force in direction i [kg·m^{-3}·s^{-1}]
$\boldsymbol{g}$	acceleration due to gravity [m·s^{-2}]
g_i	distribution function for total enthalpy in direction i [kJ·kg^{-1}]
g_i^{eq}	equilibrium distribution function for total enthalpy in direction i [kJ·kg^{-1}]
H	total enthalpy [kJ·kg^{-1}]
H_l	total enthalpy corresponding to the liquids temperature [kJ·kg^{-1}]
H_s	total enthalpy corresponding to the solidus temperature [kJ·kg^{-1}]
h_{sl}	latent heat [J·kg^{-1}]
λ	thermal conductivity [W·m^{-1}·K^{-1}]
L	characteristic length [m]
m_i	distribution function in direction i
m_i^{eq}	equilibrium distribution function in direction i
m_i^{heq}	non-equilibrium distribution function in direction i
Nu	Nusselt number
n_i	distribution function for temperature in direction i [K]
n_i^{eq}	equilibrium distribution function for temperature in direction i [K]
p	pressure [Pa]
Pr	Prandtl number
Q	heat source [J]
Ra	Rayleigh number
Ste	Stefan number
t	time [s]
t^*	dimensionless time
T	temperature [°C]
T_0	initial temperature [°C]
T_{low}	temperature at wall [°C]
T^*	dimensionless temperature
$\boldsymbol{u}$	velocity [m·s^{-1}]
$\boldsymbol{u}_s$	velocity of solid [m·s^{-1}]
V	volume [m^3]
x, y	coordinates [m]
x^*, y^*	dimensionless coordinates

Greek symbols

α	thermal diffusivity [m^2·s^{-1}]
β	thermal expansion coefficient [1·K]
μ	dynamic viscosity [kg·m^{-1}·s^{-1}]
ν	kinetic viscosity [m^2·s^{-1}]
ω_i	weight coefficient in direction i
Ω_i^s	additional collision term
ρ	density [kg·m^{-3}]
τ_f	dimensionless relaxation time for density distribution function
τ_g	dimensionless relaxation time for total enthalpy distribution function
τ_n	dimensionless relaxation time for temperature distribution function
ψ	volume fraction of liquid
σ	standard deviation of temperature

Subscripts

ave	average
b	battery
$\bar{i}$	opposite direction of direction i
PCM	phase change material

[16] firstly proposed a LB model for solid-liquid phase change based on the enthalpy method and solved the phase change problem successfully. Based on this, Huber et al. [17] combined the flow field and temperature field, with which the heat and mass transfer behaviors of phase change in a cavity were revealed. However, Huber's phase change LB model needed large amount of iterations in each time step to obtain the temperature and liquid fraction. To overcome this, Eshraghi and Felicelli [18] established an implicit LB model for phase change problem. They used two kinds of evolution equation. One was the original evolution equation to obtain the temperature field without phase change. Another was used to solve the region undergoing phase change. Feng et al. [19] extended Eshraghi and Felicelli's model to the problem of phase change by convection. Nonetheless, the implicit LB model can't solve the case that the liquidus temperature is equal to the solidus temperature. As a result, Huang et al. [15] proposed a phase change model based on total enthalpy, and temperature was obtained from total enthalpy directly. Based on this, Huang et al. [20,21] extended the total enthalpy-based LB model to the multiple-relaxation-time (MRT) scheme and adaptive mesh. In our previous work, based on Huang's LB model, the heat flux boundary condition with three kinds of distribution has been considered and the temperature field has been revealed [22]. Moreover, the phase change LB model is applied to solve the phase change problem in porous media as well, including the representative elementary volume (REV)-scale [23,24] and pore-scale [25,26]. Except the enthalpy-based method, the phase-field method [27] and immersed boundary method [20] for LB have been established as well, which are more complex.

In this paper, in order to keep the temperature of battery in cold-temperature environment, a LB model for BTM has been established. The rest of this paper is constructed as follows. In Section 2, the macroscopic conservation equations and corresponding LB model are developed. The effects of heat conductivity, latent heat and environmental temperature on thermal performance of BTM have been investigated in Section 3. The summary is presented in Section 4.

2. Numerical model

The schematic of PCM based BTM is shown in Fig. 1(a), where ABEF represents half part of battery and AF is the symmetry condition. BCDE is filled with PCM, where BC and ED are adiabatic. The length of AB is 13 mm, which is equal to that of BC. The height of the battery, AF, is 65 mm. At $t > 0$, the temperature at CD suddenly decreases to T_{low}, which is lower than the initial temperature of battery, T_0. The thermal contact resistance between PCM and battery is ignored in this paper. The numerical region shown in Fig. 1 (a) is divided into two parts, the battery region and PCM region. For the PCM region, the macroscopic quantities are obtained from the total-enthalpy based LB model, and the temperature field is revealed using another thermal LB model. The heat transfer