ANALYSIS OF HEAT AND MASS TRANSFER MECHANISM DURING THERMAL ENERGY STORAGE AND TEMPERATURE REGULATION

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Abstract: *To strengthen the heat and mass transfer capacity and improve the temperature regulation rate, potential storage is taken as the research object in this research to study the heat energy storage of the battery in the low temperature environment. Lattice Boltzmann method is adopted to study the heat energy storage influence mechanism of the temperature regulation system of the low temperature phase-change materials. In addition, the influence of different physical parameters (thermal conductivity and latent heat of phase change) on the thermal insulation of the system in the process of temperature control is revealed. The results show that the mechanism of heat and mass transfer in the process of heat storage and temperature control is related to the different physical properties of phase-change materials. The decrease of thermal conductivity and the increase of latent heat of phase-change materials will greatly increase the effect of heat energy storage. Therefore, under the action of phase change latent heat, phase change material can effectively extend the holding time of the battery in the low temperature environment.*

Key words*: Potential storage; Battery; Thermal conductivity; Latent heat of phase change*

1. Introduction

The development of human society can’t be separated from the use of energy. With the progress of human beings, the social demand for energy is constantly increasing [1]. The world's energy resources are mainly non-renewable resources (coal and oil). A large amount of carbon, sulfur, and other elements released after combustion are discharged into the environment in the form of carbon dioxide, sulfide, and other compounds. With the shortage of limited resources, environmental pollution is becoming more and more serious [2, 3]. At this time, wind energy, solar energy, and other clean energy come into being. However, due to the limited energy exploitation technology under natural conditions, the energy utilization is uneven and unstable. Therefore, in order to balance the unreasonable energy supply and energy loss in many energy utilization systems and avoid unnecessary large amount of energy waste, energy storage technology emerges at the historic moment, that is, heat energy storage.

Heat energy storage is divided into two parts, first, the sensible heat storage, second, latent heat (LH) storage. Where, LH storage is to take solid-liquid phase change material (PCM) as the energy storage medium and adopt the material to absorb or release heat during phase change to store energy

[4-6]. LH storage is characterized by large energy storage density, flexible design, and easy management. It has a practical development prospect in alleviating the problem of energy shortage [7-9]. In this research, on the basis of LH storage, lattice Boltzmann model is established through temperature regulation of low-temperature PCMs to explore the heat transfer and mass transfer mechanism of heat storage of the system, providing reference for the improvement of heat storage.

2. Methods

In order to study the thermal insulation property of the PCM, a numerical control model of temperature control is established based on lattice Boltzmann method, and fatty acids are selected as PCMs. The thermophysical properties of batteries and fatty acid phase change materials are shown in Tab. 1.

Table 1 Thermal properties of batteries and fatty acid phase change materials

Material	λ_0	c_p	ρ	μ	h_{slo}	β
Battery	4	1000	2600	-	-	-
Fatty acids	0.4	1740	940	$9.2*10^{-4}$	198000	10^{-4}

The reference physical properties are used to assist the analysis, and the differences of physical properties of solid-solid PCMs and liquid-liquid PCMs are ignored to study the influence of the thermal physical properties of fatty acids. On this basis, a schematic diagram of temperature control of PCM battery at low temperature is established, as shown in Fig. 1. The height (AB) of the system is 67mm. AB is taken as the axis of symmetry, where the length of AC and EC are equal, both 14mm. The ECDF area is the PCM, and the ABCD area is the battery. At the beginning of the simulation, the temperature on one side of the PCM drops to the cold wall temperature, at which point the cold wall temperature is less than the temperature of PCM. Other walls remain adiabatic and ignore the contact thermal resistance in this environment.

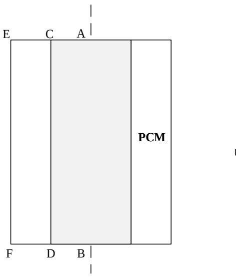

Figure. 1. Schematic diagram of temperature control of phase change material battery at low temperature

The phase change materials involved in this research are all regarded as incompressible and Newtonian fluids, and their mass and momentum conservation equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

$$\frac{\partial\ (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla \rho + \nabla \cdot (\mu \nabla u) + F \tag{2}$$

As shown in above, , u, t, and p represent density (kg/m^3), velocity (m/s), time (s), dynamic viscosity (Pa/s), and pressure (N/m^2). And F is volume force applied to the fluid (N/m^3).

$$\rho \frac{\partial H}{\partial t} + \rho \nabla \cdot (Hu) = \nabla \cdot (\lambda \nabla T) \tag{3}$$

Where, H is enthalpy (J/kg).

In this study, lattice Boltzmann equation is shown below:

$$f_i(x + e_i \Delta t, t + \Delta t) - f_i(x, t) \equiv \Omega(x, t) + \Delta t F_i \tag{4}$$

Where, e_i is discrete velocity (m/s), f_i is function of density distribution (kg/m^3), F_i is discrete term of external force in velocity space (kg/m^3·s^{-1}), and Ω is the collision term.

$$g_i(x + e_i \Delta t, t + \Delta t) = g_i(x, t) - \frac{1}{\tau_g}\left[g_i(x, t) - g_i^{eq}(x, t)\right] \tag{5}$$

In equation (5), g_i represents the distribution function of total enthalpy (J/kg), and g_i^{eq} represents the corresponding function of equilibrium distribution (J/kg).

There is no flow state inside the cell, so only the heat transfer equation needs to be derived. The equation of energy conservation of the battery is shown below.

$$\frac{\partial T}{\partial t} = \nabla \cdot (\alpha_b \nabla T) \tag{6}$$

Where the subscript “b” is the battery. The corresponding lattice Boltzmann evolution equation is shown in Eq. (7), and equation of temperature equilibrium distribution is shown in Eq. (8).

$$n_i(x + e_i \Delta t, t + \Delta t) = n_i(x, t) - \frac{1}{\tau_g}\left[n_i(x, t) - n_i^{eq}(x, t)\right] \tag{7}$$

$$n_i^{eq} = \omega_i T \tag{8}$$

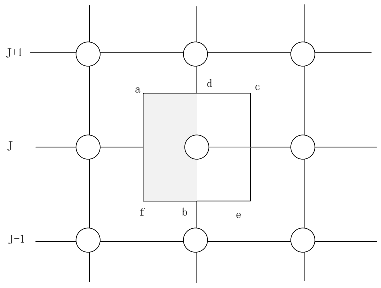

Figure 2. Schematic diagram of temperature control of phase change material battery at low temperature

Fig. 1 shows battery temperature control of PCM that at intermediate contact boundary, the battery and PCM need to exchange information, and the battery and PCM need to apply two sets of lattice methods

As shown in Fig. 2, the control body of the lattice node of acef is taken as an example. In the left half of the control body, adbf belongs to the battery area. In the right half, dceb belongs to the phase change material region. Taking db as interface, energy conservation is constructed in adbf region, and the discrete format of Eq. (9) can be obtained. Similarly, energy conservation is constructed in the dceb region, and the discrete format of Eq. (10) can be obtained. Q is the heat exchange through the interface db. The following two equations can be combined to obtain the temperature value at the next moment.

$$(\rho C_P)_P \frac{\Delta x^2}{2}(T_{i,j}^{t+\Delta t} - T_{i,j}^{t}) = \lambda_b \Delta x \Delta t\left(\frac{T_{i,j}^{t} - T_{i-\Delta x,j}^{t}}{\Delta x} + \frac{1}{2}\left(\frac{T_{i,j}^{t} - T_{i,j+\Delta x}^{t}}{\Delta x} + \frac{T_{i,j}^{t} - T_{i,j-\Delta x}^{t}}{\Delta x}\right)\right) - Q \tag{9}$$

$$(\rho C_P)_{PCM} \frac{\Delta x^2}{2}(T_{i,j}^{t+\Delta t} - T_{i,j}^{t}) = \lambda_{bCM} \Delta x \Delta t\left(\frac{T_{i,j}^{t} - T_{i+\Delta x,j}^{t}}{\Delta x} + \frac{1}{2}\left(\frac{T_{i,j}^{t} - T_{i,j+\Delta x}^{t}}{\Delta x} + \frac{T_{i,j}^{t} - T_{i,j-\Delta x}^{t}}{\Delta x}\right)\right) + Q \tag{10}$$

As the battery runs, it releases heat, causing the battery itself and the PCM to warm up. Before the simulation starts, it is assumed that all the PCMs have become liquid and the battery has stopped working at the initial time of calculation, so as to explore properties of thermal insulation of PCMs. And phase change temperature of PCM on the right wall surface is fixed at T_m, and battery temperature is evenly distributed and maintained at T_0, where T_0 is greater than T_m. Thus, the convergence benchmark obtained after steady-state calculation of its working condition is as follows:

$$\frac{\Sigma\left|\Gamma^{t+\Delta t} - \Gamma^{t}\right|}{\Sigma\Gamma^{t}} < 10^{-9} \tag{11}$$

Where, Γ is temperature and velocity. Then the system variables are dimensionless again:

$$T^{*} = \frac{T - T_{m}}{T_{0} - T_{m}} \tag{12}$$

$$t^{*} = \frac{\alpha_{b} t}{L^{2}} \tag{13}$$

$$Ra = \frac{g\beta(T_{0} - T_{m})L^{3}}{v_{PCM}\alpha_{PCM}} \tag{14}$$

$$Ra = \frac{C_{pPCM}(T_{0} - T_{m})}{h_{s1}} \tag{15}$$

$$\psi_{\lambda} = \frac{\lambda}{\lambda_{0}} \tag{16}$$

$$\psi_{\lambda} = \frac{h_{s1}}{h_{s10}} \tag{17}$$

The distance AB in figure 1 is selected as the characteristic length, where the TC of the PCM is between 0.2 and 0.3 W/m·K^{-1}, and the LH of phase change is between 185000 and 205000 J/kg. Initial temperature T_0 of the battery is 10 ° C (=1) higher than that of T_m, and the temperature range of dimensionless environment after cooling is between -1.5 ºC and -0.5 ºC.

$$Nu_{ave} = \frac{1}{L}\int_{0}^{L}(Nu)_{x=0}dy = \frac{1}{L}\int_{0}^{L}\left(\frac{q}{\lambda\partial T / \partial x}\right)_{x=0} dy \tag{18}$$

The number of Nusselt is obtained from Eq. (18). And the contact surface CD in Fig. 1 replaces the left wall surface of the system.

$$T^{*}_{ave} = \frac{\int_{s} T^{*}\mathrm{ds}}{\int_{s} ds} \tag{19}$$

$$\sigma = \sqrt{\frac{\int_{s}(T^{*} - T^{*}_{ave})^{2}ds}{\int_{s} ds}} \tag{20}$$

Where, S is the battery area (m^2), and the mean temperature and temperature standard deviation of the battery are obtained from Eq. (19) and Eq. (20). The solution region is ABEF in figure 1. In this research, the grid system is selected as 52×130, 78×195, 104×260, and 130×325 (ψ_λ=1, ψ_h=1, T_c^*=-1) for solution, and the grid Boltzmann model is tested for independent solution. The results show that when the grid system is encrypted from 104×260 to 130×325, the average relative error of Nusselt number between them is less than 1%. Therefore, the grid system used in this research is 104 × 260.

3. Results

3.1 Thermal conductivity

The effect of the TC of PCM on thermal insulation performance of battery temperature control system is as follows.

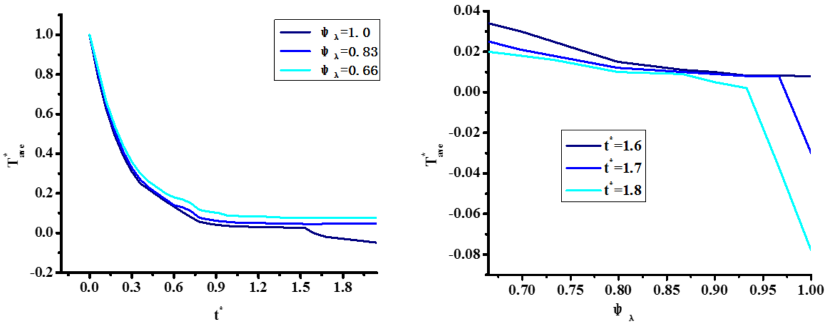

Figure 3. Battery average temperature curve

Fig. 3 shows the curve of average temperature change of battery. ψ_λ is between 0.66 and 1. In the initial process, due to the fact that most of the PCMs are liquid phase, the temperature of the battery decreases rapidly based on the influence of natural convection. When the PCM begins a liquid-solid phase change, the LH stored inside is released, and temperature drop rate of the battery gradually slows down. Different from heat dissipation, the battery temperature control system in a low-temperature environment needs to maintain the temperature. Therefore, increasing the TC of the PCM will accelerate heat dissipation of battery to the environment.

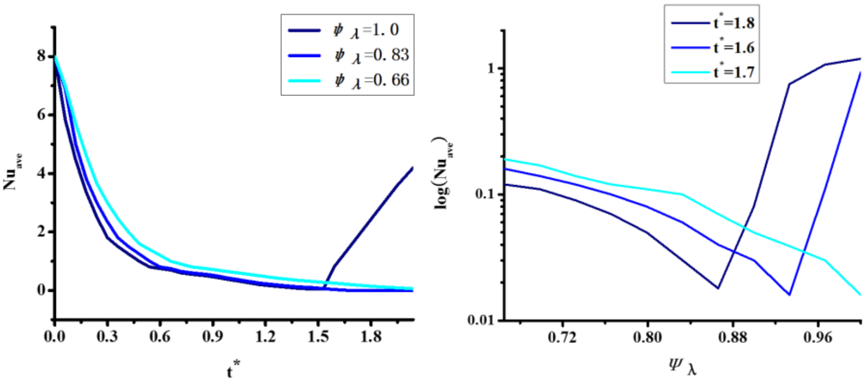

Figure 4. CD surface average Nusselt number of PCM with different thermal conductivity

Fig. 4 shows the average Nusselt number of CD surface under different TC of PCMs. Average Nusselt number is the dimensionless temperature gradient on the CD surface. It can be observed that the main source of heat transfer on the CD surface in the initial stage is convection. When the heat diffuses to the environment, PCM gradually transforms from the liquid phase to the solid phase, and phase interface gradually moves to the direction of the battery. The natural convection area begins to decrease, so the heat transfer of interface decreases, and the average Nusselt number decreases. When phase change material is completely transformed into solid phase, heat transfer on wall increases rapidly, accelerating the increase of the average Nusselt number. The average Nusselt number gradually flattens, when TC reduces.

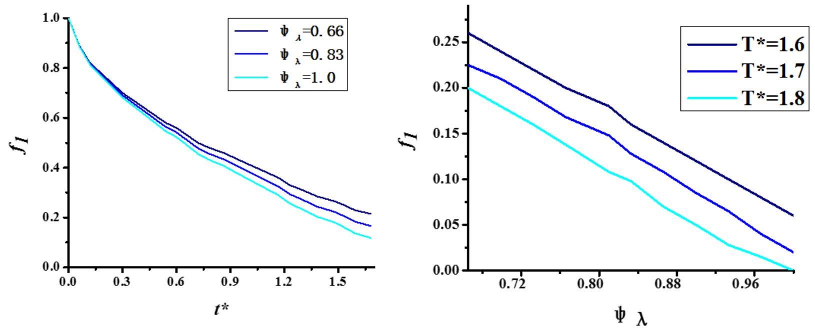

Figure 5. Curve of total liquid phase rate under TC of different PCMs

Fig. 5 shows the change curve of total liquid phase ratio under different TC of PCMs. When TC increases gradually, the decline rate of liquid phase rate increases gradually.

3.2 LH of phase change

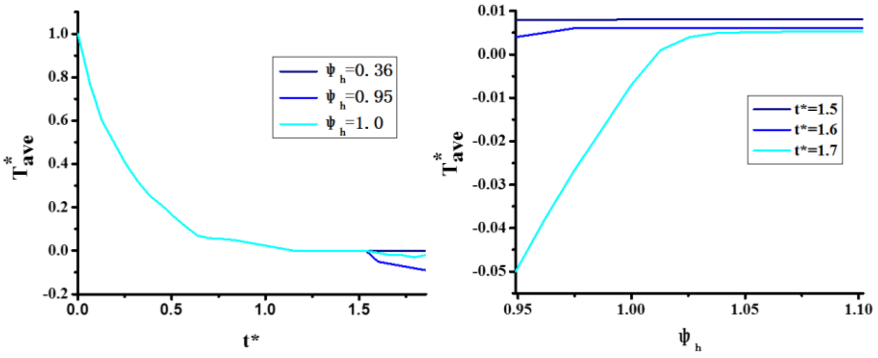

Figure 6. The changes of average temperature of battery

Fig. 6 shows the variation curve of the average battery temperature with ψ_h. As mentioned above, the average temperature of the battery decreases gradually before the PCM is completely converted to solid phase. It can be concluded that, at the same time, the average temperature difference of the battery under different phase change LH is small. However, the temperature of the battery drops rapidly after PCM is completely converted to solid. Therefore, solidification time of PCM can be effectively extended by large LH of phase change.

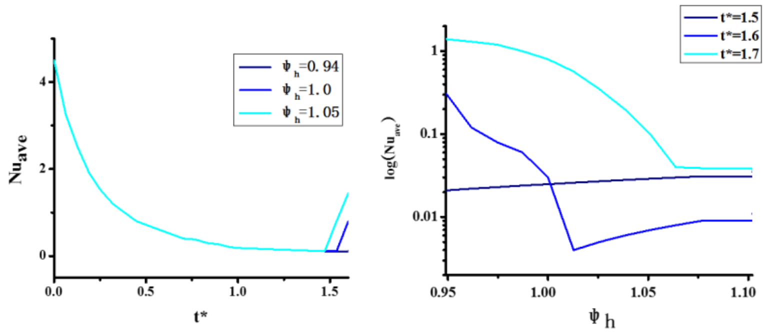

Figure 7. The average Nusselt number curve for the CD surface

Fig. 7 represents change curve of the average Nusselt number on the CD surface. After the phase change material is completely solidified, the average Nusselt number at the contact surface increases rapidly without the effect of LH of phase change, and heat transfer increases, so that temperature of the battery drops rapidly. Before the PCM solidifies completely, the LH of PCM could be increased to increase heat transfer at the contact surface.

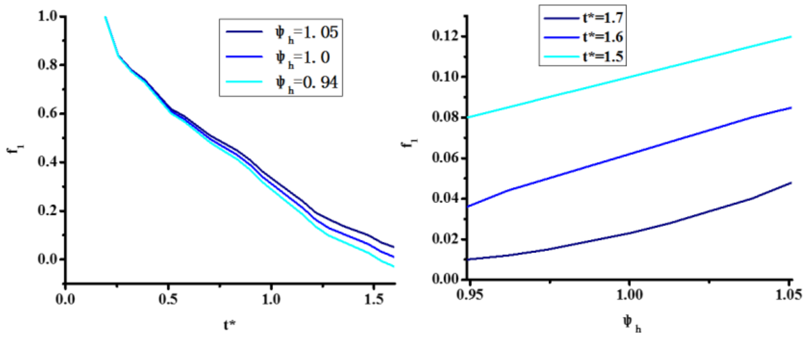

Figure 8. Liquid phase rate curve of LH of different PCMs

Fig. 8 shows the curve of liquid phase rate under LH of different PCMs. It is found that increasing LH of PCM can improve thermal insulation performance of PCM. As mentioned above, reducing the TC of PCM and weakening heat transfer property of the PCM can improve the insulation capacity of the system. However, considering that the temperature control system needs to heat the battery at high temperature, if TC is insufficient, heat transfer property of temperature control system will be limited, so that system can’t have both heat dissipation and heat preservation functions. What’s more, the LH of phase change can be increased to maintain the working temperature of the battery for a long time when the temperature control system dissipates heat. The change of TC is usually the addition of low TC materials for heat insulation, so that the mass of PCM per unit volume decreases, and LH decreases relatively. Therefore, the primary task of temperature control system of low temperature PCMs is to ensure LH of phase change.

4. Discussion

Heat storage and heat transfer mechanism are discussed, and the constant temperature characteristics of fatty acid PCMs are analyzed. The thermal insulation performance of the temperature control system of phase change material under low temperature environment is studied, and the influence rule of different physical parameters and environmental temperature on the temperature control performance is revealed. In the temperature control process of low temperature of PCM, under the action of the LH of the phase change, the holding time of the battery in the low temperature environment can be effectively extended by adopting PCM, and a small temperature standard deviation of battery can be maintained.

As mentioned above, the TC of PCMs is generally low. According to Fourier's heat conduction rule, the value of heat transfer rate is correlated with the thermal conductivity. The lower the TC is, the slower the propagation rate will be, which will reduce the storage rate and heat dissipation rate of heat energy storage and increase the time required for heat energy storage. Therefore, the basic heat and mass transfer properties of PCMs can be enhanced and the rate of LH storage can be improved by utilizing heat storage and mass transfer mechanism in the process of temperature control. Under the current demand of high energy storage density, only a single heat transfer form can’t meet the needs of the technology. In the future, multiple enhancement methods should be developed for common heat transfer enhancement. In view of the low TC of some PCMs, carbon materials such as high TC metal particles, expanded graphite, and graphene can be added, and high TC fins can be inserted, or the heat transfer structure can be designed, so as to provide reference value for the heat storage process.

5. Conclusion

One of the most effective methods for heat and mass storage is phase change energy storage. Heat energy storage can improve energy efficiency and solve the problem of uneven energy distribution in time and space. Because of its stable working temperature and high density storage characteristics, it has become the research object of experts at home and abroad. In this research, the thermal insulation performance of the battery in a low temperature environment is studied, and with the help of lattice Boltzmann method, the characteristics of temperature control of PCM are analyzed, which reveals the specific heat and mass transfer mechanism of the melting rate and temperature distribution of the PCM. Firstly, under the action of phase change LH, the use of PCMs can effectively extend the holding time of battery at low temperature. During the solidification of PCMs, the temperature standard deviation of the battery gradually decreases because of LH of the phase change, which limits temperature change of battery. When the PCM solidifies completely, the temperature standard deviation of the battery increases rapidly. Secondly, decreasing the TC of the PCM and increasing LH of PCM will prolong the holding time. Changing LH of the PCM in initial solidification stage has little influence on temperature magnitude and distribution of battery, but it will change the complete solidification time of the PCM. Considering that the PCM temperature control system needs to dissipate the heat of the battery under high temperature environment, the PCM with high LH can better meet the requirements of thermal insulation. Therefore, the decrease of TC and increase of phase change LH are beneficial to heat energy storage and enhancement of heat and mass transfer in process of temperature control, so as to improve the rate of LH storage.

6. Acknowledgement

National Natural Science Foundation of China(No.51705332).

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