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Performance optimization of battery cooling system based on phase-change latent heat energy storage

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ABSTRACT

Lithium battery energy storage system (ESS) needs high-power refrigeration equipment to maintain a comfortable operating temperature to ensure the operating performance and long-life of the batteries. But this dramatically increases the size and cost of the system. Here, we proposed a battery cooling system coupled with phase-change thermal energy storage (PHTES) unit. The PHTES unit pre-cools the cooling fluid, greatly reducing the refrigerating capacity of the chiller, thus reducing the volume and cost of the refrigeration system. In addition, we have established the lumped heat model of PHTES unit and battery liquid cooling system. Based on this model, we can optimize the storage capacity of PHTES unit and cooling capacity of chiller, thus minimizing the energy consumption and cost of the system. This work proposes a low energy consumption and low-cost thermal management method for battery ESS, and provides a simple and accurate model for the optimization of thermal management system.

Keywords: energy storage system, battery thermal management, thermal energy storage, lumped heat model

NONMENCLATURE

T	Temperature (°C)
m	Mass (kg)
c	heat capacity (kJ·kg^{-1}·K^{-1})
Abbreviations	
ESS	energy storage system
PHTES	phase-change thermal energy storage
PCM	phase change material
Symbols	
b	Battery

1. INTRODUCTION

Renewable energies such as wind and photo-electric energy have been developed rapidly to reach the goal of carbon peaking and carbon neutrality as soon as possible [1]. Energy storage system (ESS) has the function of peak-load shifting and plays a vital role in the utilization of renewable energy. [2] Because of the high energy density and long life-span, lithium batteries are widely used in ESS.

The performance of lithium-ion batteries is greatly affected by its operating temperature. Lithium battery will generate a lot of heat and rise the temperature during the operation. An increase in battery temperature will reduce battery performance and cycle life, increasing the risk of thermal runaway of the battery.[3] Therefore, to ensure the high performance, long life-span and safe operation, the ESS must have a cooling system to maintain a comfortable operating temperature for the batteries.

Currently, the battery cooling strategies can be divided into active cooling, passive cooling and coupled cooling strategies. The active cooling mainly includes air cooling and liquid cooling [4]. The air cooling and liquid cooling strategies take away the heat of batteries by convection and dissipate the heat to chiller. Due to the low heat capacity of air, the cooling capacity of air cooling is poor. Compared to air, liquid has a higher heat capacity and thermal conductivity, so liquid cooling has a better cooling capacity. The active cooling strategy depends on the cooling capacity provided by the refrigeration equipment. It dramatically increases the size and cost of the system. The passive cooling strategies mainly includes phase change material (PCM) cooling, heat pipe cooling and so on. The passive cooling strategy does not require additional refrigeration equipment. PCMs can absorb large amounts of heat

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during the phase change and maintain the battery temperature within a narrow range. Therefore, PCM cooling has a broad application prospect in battery thermal management. However, the cooling ability fails when the PCM is completely transformed.

Active cooling can take away the heat stored by the PCM, thereby restoring its cooling capacity. The battery cooling system coupled with liquid cooling and PCM cooling has the advantages of good cooling effect, good stability and low energy consumption, and has been widely studied [5-6]. Most studies install the PCM in the battery pack to absorb the heat generated by the battery, and the liquid cooling restore the heat storage capacity of PCM. Although this coupling method has a better cooling effect and temperature consistency, it will increase the volume and the structural complexity of the battery pack [7].

This study proposed a coupling cooling method that use PCM to cool the liquid in advance, thereby reducing the peak power of the refrigeration unit. When the battery is operating, the PCM works with the chiller to provide cooling capacity to the battery pack. When the battery is charged or at rest, the chiller provides cooling capacity to the PCM to restore its cold storage capacity. This coupling cooling system greatly reducing the refrigerating capacity of the chiller, thus reducing the volume and cost of the refrigeration system.

In order to consider the energy consumption and cost of the entire battery thermal management system [8], we have established the lumped heat model of PHTES unit and battery liquid cooling system. Based on this model, we can optimize the storage capacity of PHTES unit and cooling capacity of chiller, thus minimizing the energy consumption and cost of the system. This work proposes a low energy consumption and low-cost thermal management method for battery ESS, and provides a simple and accurate model for the optimization of thermal management system.

2. EXPERIMENT AND SIMULATION

2.1 Experiment set-up

The diagram of battery cooling system integrated with PHTES is shown in Fig. 1, mainly including battery pack, pump, PHTES unit and chiller. When the battery pack is in discharging, the batteries generate a lot of heat and require high cooling power to reduce their temperature. During the discharge process, the PHTES unit can pre-cool the outlet water of the battery pack, thus reducing the cooling power of the chiller, as shown in Fig.1 (a). When the battery pack is in charging, the batteries generate less heat and require less cooling power. As shown in Fig.1 (b), the chiller can provide cooling capacity to PHTES unit to restore the latent heat storage capacity of PHTES.

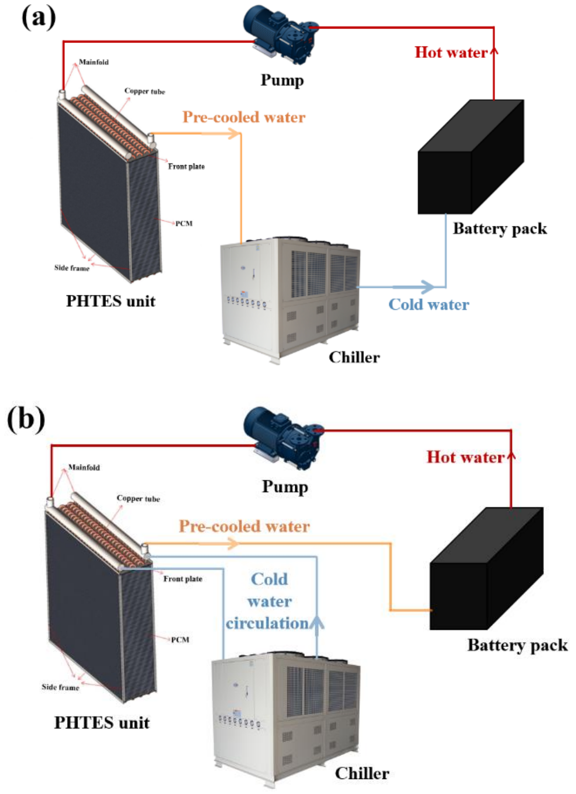

Fig. 1 (a) Discharge process of battery cooling system integrated with PHTES; (b) Charge process of battery cooling system integrated with PHTES

2.2 PHTES model

The lumped heat model of PHTES is established in this study. The structure of PHTES is tube-plate structure, as shown in Fig.2 (b). The tube is embedded in the EG/ paraffin-shaped composite PCM. The physical properties of PCM are listed in Table 1. Fig 2 (a) shows the lumped unit of the tube-plate PHTES model. In order to improve the calculation accuracy, the PCM outside the tube is divided into 4 layers. In this model, the latent heat of phase change was calculated by equivalent specific heat c_h. Therefore, the energy conservation of the PCM is specified as

$$m_{pcm}c_{pcm}\frac{dT_{pcm}}{dt}+m_{pcm}\frac{dc_h}{dt}=q_1$$

where m_{pcm} is the mass of the PCM, c_{PCM} is the specific heat capacity of the PCM, c_h is the equivalent specific heat of PCM latent heat, T_{pcm} is the temperature of the PCM, q_1 is the heat exchange between PCM and tube.

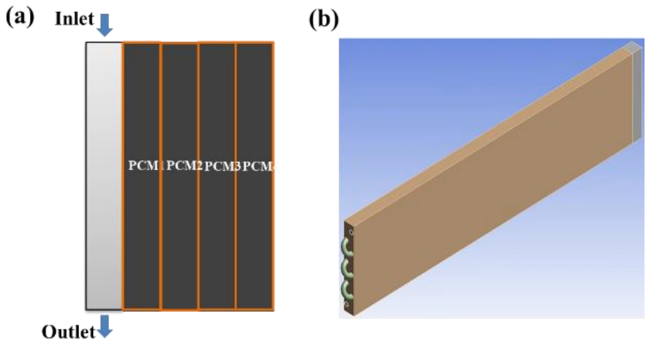

Fig. 2 (a) lumped unit of the tube-plate PHTES; (b) structure of PHTES

Table 1. Physical properties of PCM.

Physical properties	Description
Phase change range (°C)	30-33
Latent heat of fusion (kJ·kg^{-1})	200
Density (kg·m^{-3})	800
Thermal conductivity (W·m^{-1}·K^{-1})	5
Specific heat capacity (kJ·kg^{-1}·K^{-1})	1.1

2.3 *Battery model*

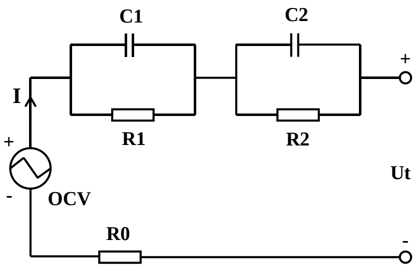

Fig. 3 Second-order equivalent circuit

A second-order RC model was used to build an electric model of the battery [1]. shows the schematic of the second-order RC circuit model. U_{ocv} represents the open voltage, R_0 represents the ohmic resistance of the battery, R1 and R2 are second-order polarization resistance of the battery, and C_1 and C_2 are capacitors parallel to R_1 and R_2. U_{ocv}, R_0, R_1, R_2, C_1 and C_2 are functions of temperature and SOC. These parameters are estimated from the DCIR data and the current data are discrete and there are sampling steps and simulation steps. Therefore, the voltages across the two polarization resistors of the model are described as below:

$$U_1(t+\varDelta t) = e^{-\frac{\varDelta t}{\tau_1}} U_1(t) - R_1(1-e^{-\frac{\varDelta t}{\tau_1}}) - I(\mathrm{t})$$

$$U_2(t+\varDelta t) = e^{-\frac{\varDelta t}{\tau_2}} U_2(t) - R_2(1-e^{-\frac{\varDelta t}{\tau_2}}) - I(\mathrm{t})$$

where U_1 and U_2 are the transient voltages across the two polarization resistors, $\varDelta t$ is time step, τ_1 and τ_2 are time const and are calculated as:

$$\tau_1 = R_1 C_1 \tau_2 = R_2 C_2$$

The discharge voltage of the battery can be expressed as Equation (4):

$$U_t = U_{ocv} - IR_0 - IR_1 - IR_2$$

where U_t is the discharge voltage of the battery, and I is the current flowing through the battery, with discharge as positive and charging as negative.

The energy conservation of the battery can be specified using Equation (7):

$$m_b c_b \frac{dT_b}{dt} = q_1 + q_2$$

where m_b is the mass of the battery, c_b is the specific heat capacity of the battery, T_b is the temperature of the battery, q_1 is the internal heat generated by the total internal resistance of the battery, and q_2 represents the heat exchange between the battery and the cooling pipe.

The internal heat q_1 is largely generated by the internal resistance of the battery:

$$q_1 = I^2(R_0 + R_1 + R_2)$$

2.4 *Validation of mode*

Fig.4 shows the comparison of PHTES unit outlet temperature between lumped heat model and finite element model. The simulation results of lumped heat model are close to those of the finite element simulation, with an average temperature deviation of only 2.2 °C. This proves the reliability of the lumped heat model.

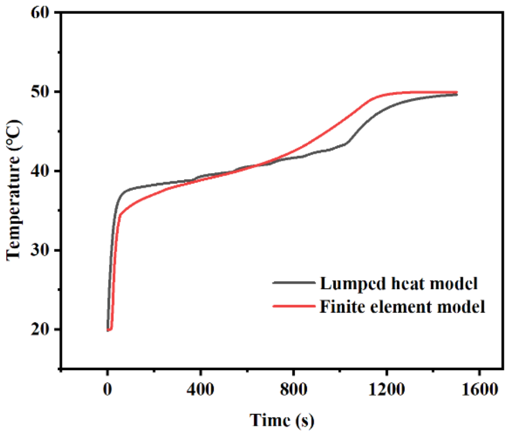

Fig.4 Validation of PHTES unit outlet temperature between lumped heat model and finite element model

2.5 *Initial conditions and control methods*

The initial temperature of the system is set at 25 °C. The battery pack was discharged at 1 C and charged at 0.5 C and rest 10min after each discharge or charge. When the temperature is higher than 40 ° C, the battery life will be shortened. Hence the maximum temperature limit of the battery pack is set as 40 °C.

The battery cooling system is an internal cycle, that is, the outlet fluid of the battery pack is the inlet fluid of the chiller. The PHTES is placed in front of the chiller so that the cooing liquid is pre-cooled by the PHTES. In the cooling system coupled with PHTES, the chiller provides cooling to the fluid during the discharge of the battery pack, and the supplies cooling to the PHTES to restore its cold storage capacity during the charge and rest process of the battery pack.

3. RESULTS AND DISCUSSION

3.1 Cooling performance of PHTES

Fig 3(a) compares the cycle operating temperature of a battery pack with and without PHTES at the same cooling power. Obviously, the temperature of the battery pack with PHTES is much lower than that of battery pack without PHTES. When the temperature is higher than 35 °C, the maximum temperature of the battery pack with PHTES remains basically unchanged. This is because the inlet temperature the battery pack is reduced during the phase change process of PHTES, so as to ensure the constant temperature of the battery pack. Fig.3 (b) shows the inlet water temperature curve of the battery cold plate. The inlet temperature of the battery system without PHTES continued to rise, reaching 44°C after 10 charge-discharge cycles. While the inlet temperature of the battery system with PHTES increased slowly when the temperature reached 33°C, and the highest inlet temperature is only 35 °C. Since the cooling power of chiller is less than the heat generated by the battery pack, the cooling water temperature continues to rise. During the phase change phase, PHTES can provide cooling capacity and absorb some of the heat of the cooling water to ensure a constant water temperature at the inlet of the battery pack.

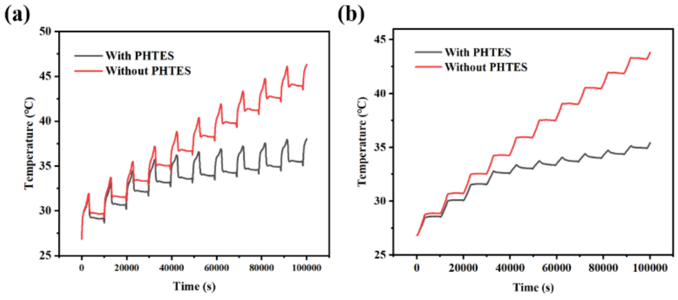

Fig. 3 (a) comparison of cycle operating temperature of a battery pack with and without PHTES at the same cooling power; (b) comparison of water inlet temperature of a battery pack with and without PHTES at the same cooling power

Fig. 4 shows the temperature of battery pack without PHTES at different cooling powers. As the power of the chiller increases, the temperature of the battery pack decreases. When the power of the chiller is increased to 150%, the maximum temperature of the battery pack can be reduced to below 40 °C. The cooling system with PHTES can keep the battery pack temperature below 40 °C at 100% cooling capacity. It proves that the battery cooling systems with PHTES can reduce refrigeration energy consumption by 50%.

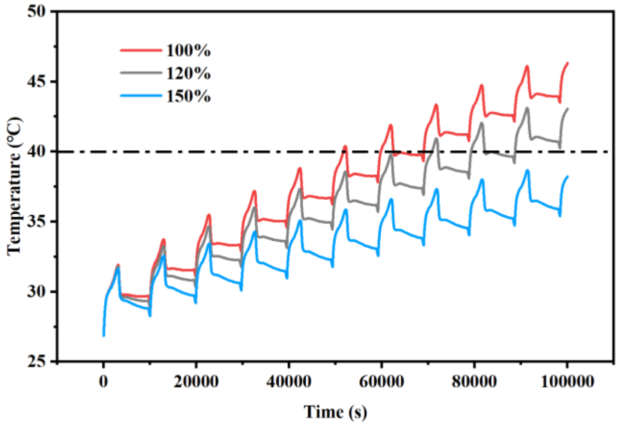

Fig. 4 Temperature of battery pack without PHTES at different cooling powers

4. CONCLUSIONS

We proposed a battery cooling system coupled with phase-change thermal energy storage (PHTES) unit. The lumped heat model of PHTES unit and battery liquid cooling system was also established. The PHTES unit can pre-cool the cooling fluid, reducing the inlet temperature of the chiller by 9 °C, so that the circulating operating temperature of the battery pack is always kept below 40 °C. While cooling system without PHTES requires 150% cooling power of the chiller to reduce the maximum temperature of the battery pack to below 40 °C. It proves that the battery cooling systems with PHTES can reduce cooling power by as much as 50%. The PHTES coupled battery cooling system greatly reducing the refrigerating capacity and cooling power of the chiller, thus reducing the volume and cost of the battery ESS. The PHTES coupled battery cooling system has great application potential in the field of battery ESS.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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