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Thermal management of 48 V standby battery for outdoor base station at cold environment

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Abstract

The standby battery for outdoor base station could not function properly at cold environment for a long time. In order to improve its performance and lengthen its life time, it was necessary to heat the battery and keep warm. This dissertation presented the heating and heat preservation method of 48 V Lead-acid battery pack for base station based on the heating plate and phase change materials at cold environment. Then, the thermal management performances of this battery pack were simulated. The results showed that the uniformity of battery temperature field was increased and the heat preservation process was lengthened effectively. And the pack kept good working condition after continuous heating and heat preservation progress. The method was simple and practicable, and it could be used on the thermal management of lithium ion battery because of its good applicability

Keywords: Battery pack; Cold environment；Phase Change Materials; Heating; Heat preservation

1. Introduction

As the information and communication technology developed, the quantity demand of outdoor base stations gradually increases. The stability and reliability of Lead-acid battery in outdoor base stations is important as it is

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used to offer the emergency power supply for other facility. However, the Lead-acid battery is easily influenced by the ambient temperature. In somewhere of north China, annually, there are more than 110 days whose average ambient temperature is lower than 0 ℃ [1]. When the temperature decreases, the viscosity of electrolyte increases and the electrolyte is difficult to penetrate into the inner layer of the plates for battery. As the results, the electrochemical reaction slows down, capacity and efficiency during the charging and discharging process get poor. What's more, the electrolyte will get solidification, which may lead to the fracture of plate and swell of battery shell. It is necessary to heat the battery and keep it warm in the cold environment.

At present, the battery thermal management system is widely used in protecting the power battery on the electric vehicle [2]. But there is little attention focus on the thermal management of outdoor standby battery pack. It may be a solution to bury the battery pack in the earth to maintain the temperature of battery. But it is complex and unpractical to restructure the station. Problem will be solved better to increase corresponding auxiliary equipment to keep the battery working at proper temperature. Consequently, there is a need for a low-cost and efficient thermal management package that provides an adequate operational temperature range to enable outdoor applications of Lead-acid battery.

During the melting / solidifying process, the phase change materials (PCMs) can store / release large amounts of heat with the latent heat and the temperature of the PCMs stays constant until the phase transition process complete [3]. As its high latent heat of phase change and its melting point located in the working temperature arrangement of battery, the paraffin is the most widely used in battery thermal management [4-5].Thermal management based on the PCMs used in power battery cooling can delay the temperature rise after absorbed the heat generated by battery and heat from the environment [6]. Similarly, the PCMs can be used in keeping the battery warm for a relatively long time in cold environment after absorbing the heat from the active heater. The research of Wang showed that the effect of PCMs on improving the uniformity of temperature distribution and restraining temperature changing was obvious [7]. So, the combing of PCMs and active heater will improve the temperature uniformity of battery and prolong the time of keeping warm, compared with the single active heating method based on heater. This paper presented the heating and heat preservation method of 48 V Lead-acid battery pack for base station based on the heating plate and PCMs at cold environment.

2. Structure

2.1. Physical problem

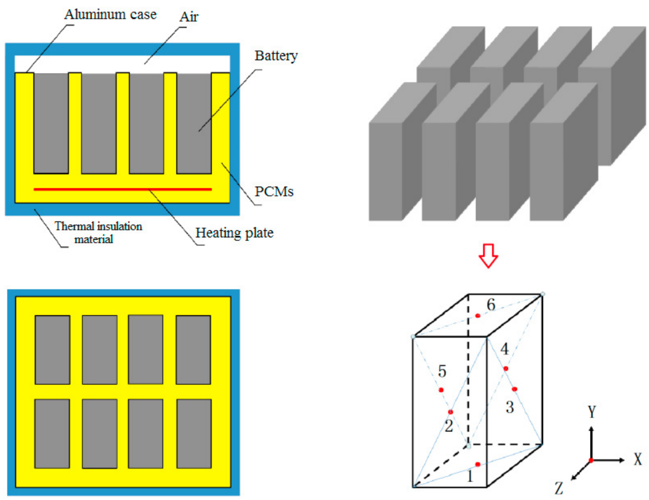

Fig. 1 Structure of battery pack

The structure of battery pack was shown in Fig. 1. The pack consists of 8 (2 in parallel, then 4 in series) Sony LC-P1220 Lead-acid batteries, PCMs and heating plate. The voltage of each battery is 12V , the capacity is 20Ah and the size is 0.18×0.08×0.17 m^3. As the optimum working temperature range of Lead-acid is 20~30 ℃, the PCMs used in the battery pack is n-octadecane, whose melting point is 28 ℃. The batteries are surrounded with the PCMs. In order to increase the heat transfer and avoid leak of PCMs, the aluminum case is used. And thermal insulation material covers the pack will reduce the heat dissipation and prolong the heat preservation process. The parameters of relevant materials used in the simulation are listed in Table 1.

The model was meshed by Gambit and simulated by FLUENT 15. The theoretical model is developed based on the assumptions: physical property parameter of PCMs was constant during the phase change process.

Table 1 Parameters of relevant materials in the pack

	Density ($kg \cdot m^{-3}$)	Heat conductivity coefficient ($W \cdot m^{-1} K^{-1}$)	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Latent heat ($kJ \cdot kg^{-1}$)
Lead-acid battery	2860	1.3	800	
N-octadecane [9]	778	0.21	1900	244
Thermal insulation material	200	0.02	500	
Aluminum	2719	202.4	871	

2.2. Governing equations

The heat generated by heating plate is equal to the heat absorbed by each part in the battery pack and the heat dissipation on the pack surface. The energy conservation equation is:

$$q_{heat} = q_b + q_{PCMs} + q_{Al} + q_{plate} + q_{ins} + q_{dis} \quad (1)$$

where q_b, q_{PCMs}, q_{AL}, q_{plate}, q_{ins} is the heat absorbed by the battery, PCMs, aluminum case, heating plate and thermal insulation material, respectively. q_{heat} is the heat generated by the heating plate in the form of electrical heating. And the q_{dis} is the heat dissipation of pack to the ambient.

As the heat generated by the battery in the standby state can be ignored, the energy conservation equation of cell and PCMs can be expressed as:

$$\frac{\partial}{\partial t}(\rho c_p T) = \lambda \nabla^2 T \quad (2)$$

where t, λ, ρ, c_p, and T is the time, heat conductivity coefficient, density, specific heat capacity and temperature, respectively.

According to Newton's law of cooling, the boundary equations in each direction can be expressed as follows:

$$-\lambda \nabla T = h(T_{out} - T_0) \quad (3)$$

where T_{out}, T_0 and h is the temperature of battery pack surface, ambient temperature, and convective heat transfer coefficient, respectively. The value of h in different surface of battery pack is calculated as reference [8].

The heat dissipation of pack was in the form of natural convection between pack surface and ambient. In order to keep the temperature of battery around the phase change temperature of PCMs for several days, the mass of PCMs can be calculated by dividing the total heat transfer q_{dis} with latent heat of PCMs. As the volume of PCMs is calculated the size of battery pack is conformed. As Fig.1 showed, the space between adjacent batteries is 0.03 m and 0.04 m in X and Y direction, respectively. The space between battery and thermal insulation layer 0.045 m, 0.05 m and 0.05 m in X, Y and Z direction, respectively. The thickness of thermal insulation layer is 0.02 m.

3. Results and discussion

3.1. Effect of arrangement of semiconductor thermoelectric device

The ambient temperature of a region changes in the cycle of day and night in one season. In this simulation, the sinusoidal function is used to describe the ambient temperature. For instance, $T_0 = -10 + 5 \cdot \sin(2 \cdot t / 3600 / 24 - 9$

/ 12) indicates the average ambient temperature is -10 ℃, the maximum temperature difference of day and night is 10 ℃ and the maximum temperature and minimum temperature appears at 3 pm and 3 am, respectively.

The temperature of battery pack versus time with different environment temperature is showed in Fig.2. The initial temperature of pack is 28 ℃ and the PCMs is in liquid state. During the natural convection process with ambient, the maximum temperature of battery pack decreases. In the first stage, the temperature decreases slowly as the PCMs is in the process of solidifying and it releases large heat with latent heat to restrain the declining of battery temperature. In the second stage, the battery temperature decreases suddenly as the majority of PCMs in the pack is in solid state and the sensible heat of PCMs can't prevent the battery temperature declining. In the last stage, the temperature approaches the ambient temperature slowly as the temperature of difference of pack surface and ambient is small and the heat dissipation is small. In the whole process, the battery temperature decreases periodically because of the periodical ambient temperature.

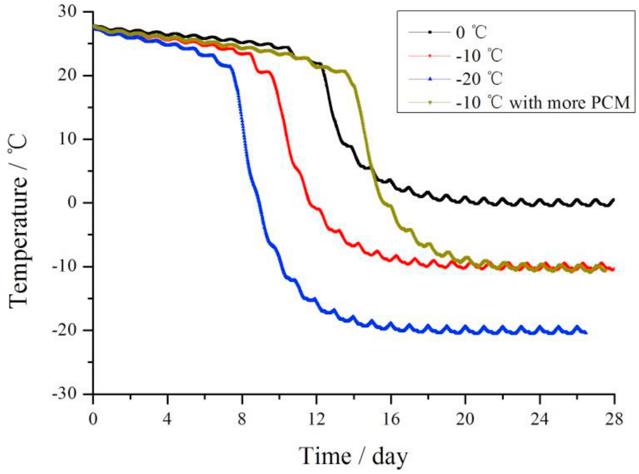

Fig. 2 Temperature of battery pack versus time with different environment temperature

As the battery temperature decreases rapidly and the heat conductivity coefficient of PCMs is small, in order to keep the battery temperature higher than 20 ℃ and decrease the temperature difference in the battery pack, the heating plate should heat the PCMs before the minimum temperature of monitor point on the battery surface declining to 23 ℃. And the heating should stop before the maximum temperature of monitor point higher than 30 ℃, as the optimum working temperature range of Lead-acid battery is 20~30 ℃.

3.2. Effects of area and arrangement of heating plate

The area and arrangement of heating plate influence the temperature distribution and time of heating and heat preservation process. In order to protect the battery from being over heated which result from the high temperature heating plate during the heat process, as well as increase the PCMs' heat absorbing, the heating plate should be arranged far from the batteries. The heating plate was arranged horizontally under the batteries or vertically around the batteries. The heating plate is made by cast aluminium alloy and the thickness is 3 mm. The maximum heating power is 40 kW • m^{-2}. In this section, battery packs with 7 different combinations of different heating plate area and arrangement was simulated. The combinations are showed in the Table 2.

Table 2. The combinations of heating plate size and arrangement

case	1	2	3	4	5	6	4
Area (m^2)	0.25	0.16	0.09	0.04	0.25	0.16	0.09
Arrangement	Horizontal and under the batteries				Vertical and around the batteries		

In order to know about the temperature distribution of battery pack, we monitored the temperature of 6 points in the pack, as well as the maximum / minimum temperature of all the batteries. The locations of 6 monitor points are showed in Fig.1. In this section, the ambient temperature is $T_0 = 10 + 5 \cdot sin\ (2 \cdot t / 3600 / 24 - 9 / 12)$ and the total heating power of heating plate is 200 W. The upper and lower temperature limit of heating process is 23 ℃ and 30 ℃, respectively.

The Fig.3 shows the battery temperature of case 2 and case 5 during the heating and heat preservation process. Comparing the Fig.3(a) and Fig.3(c), we can see the temperature increasing rate of battery pack with different heating plate arrangement shows the different trends. And the maximum battery temperature difference of case 2 appears at the end of heating process and that of case 5 appears at middle period. Because the natural convection rate in the PCMs caused by gravity with vertical heating plate is higher than that of case with horizontal heating plate. What's more, it leads to different heating time in the heating process. Comparing the Fig.3(b) and Fig.3(d), we find that the battery temperature of case 2 after heating process increases continually for 3 days and that of case 5 decrease slowly. When the heating plate is horizontal, at the end of heating process, the increasing rate of battery temperature is biggest during the whole heating process and the temperature gradient of PCMs is largest. During the heat preservation process, the heat transfer between battery and PCMs continues. It leads to the temperature rising continually.

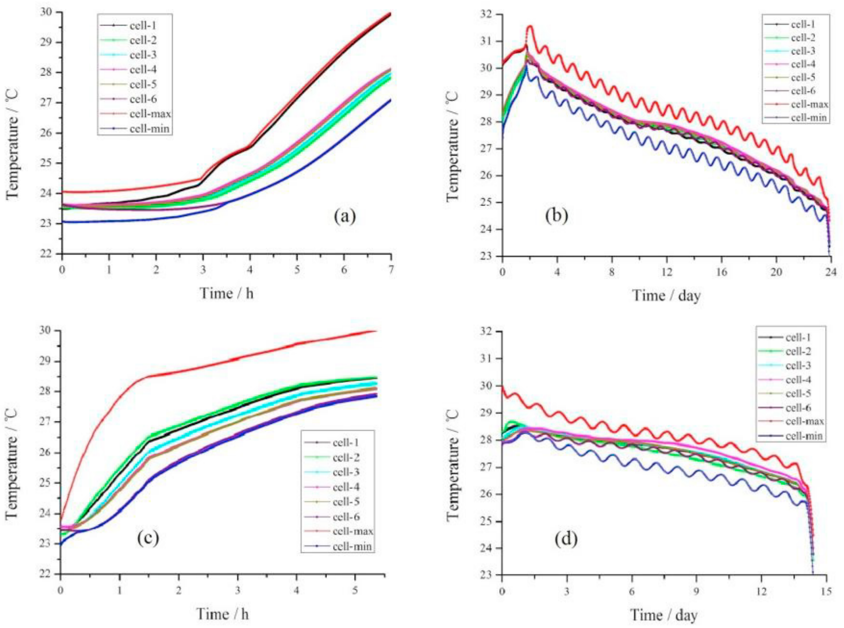

Fig. 3 Temperature of monitoring point versus time, (a) case 2 heating process, (b) case 2 heat preservation progress, (c) case 5 heating process, (d) case 5 heat preservation progress

The Fig.4(a) and Fig.4(b) shows the heating process time and heat preservation process time of different case, respectively. It indicates that the longer the time of heating process, the longer the time of heat preservation process is. As the heating power is same, the amount of heat absorbed by the PCMs is in direct proportion to the heating time. And the time of heat preservation time is determined by the amount of heat absorbed by PCMs. What's more, we find that as the area of heating plate increases, the time of heating process and heat preservation process decreases. When the area of heating plate is equal, the time of heat preservation process of case with horizontal heating plate is longer than that of case with vertical heating plate. As the Fig.4(c) shows, the maximum temperature difference of different cases during the heat preservation are all lower than 2 ℃ and similar. However, the difference between maximum temperature difference of different cases in heating process is obvious. Therefore, in order to improve the temperature uniformity and prolong the heat preservation process, the horizontal heating plate is appropriate. As the heat preservation time of case 1 and case 2 is similar and the heating time of case 1 is twice of that of case 2, the case 2 is best chose to decrease the power consumption.

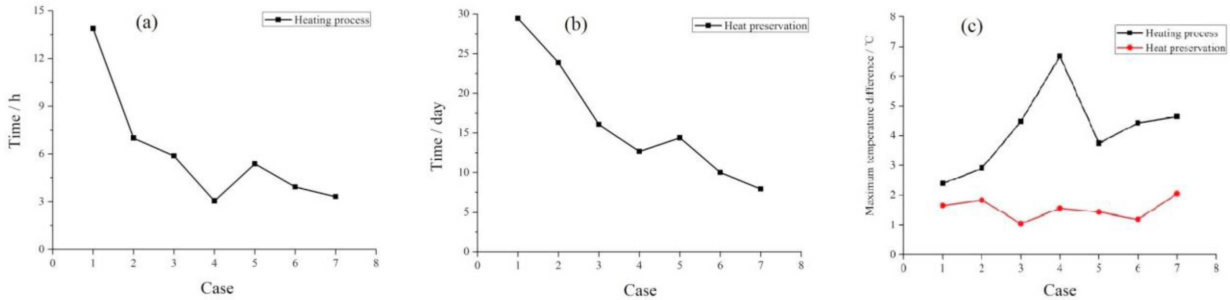

Fig. 4 Time of heating process (a), time of heat preservation progress (b) and maximum temperature difference (c) versus case with different heating plate setting

3.3. Effects of heating power

In this section, the effect of different heating power on thermal management is researched. The heating plate setting of case 2 is used in the simulation. The initial temperature of the pack is 28 ℃, and the average ambient temperature is -10 ℃. When the battery minimum temperature declines to 23 ℃ after natural convection, the pack is heated with 100 W, 200 W, 500 W and 1000 W, respectively, until the maximum temperature reaches 30 ℃. The Fig.5 shows the temperature variation of different monitors in pack with different heating power. It indicates that the time of heating process decreases with increasing heating power and the heat absorbed by the PCMs decreases from 3.2 KWh to 0.63 KWh. What's more, the maximum temperature difference increases from 1.93 ℃ to 5.49 ℃. It indicates that the uniformity of temperature field in the pack declines with the increasing heating power. In order to increase the system stability, shorter heating process is needed. Therefore 200 W heating power is appropriate to balance the heating time and temperature uniformity.

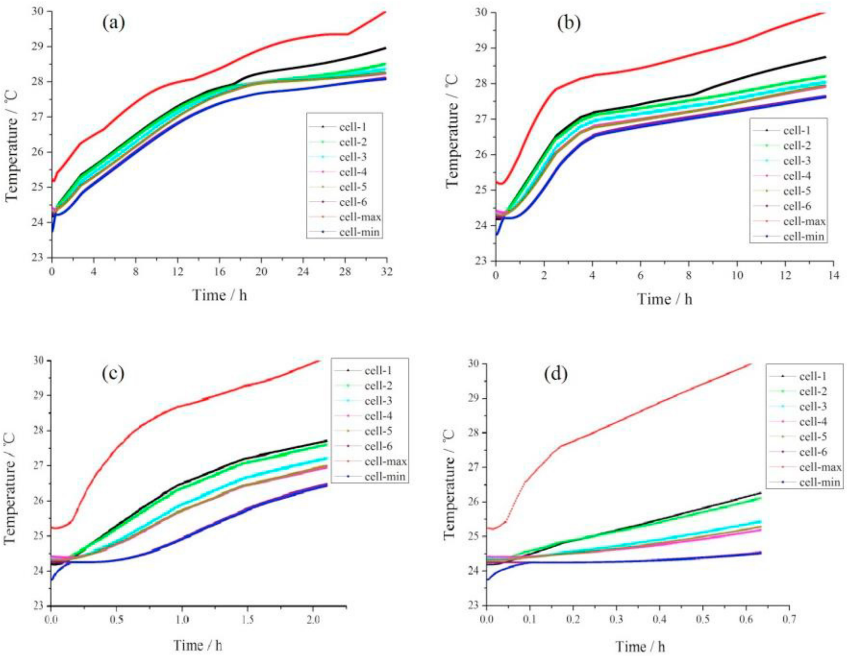

Fig. 5 Temperature variation of monitoring points with different heating power: (a) 100 W, (b) 200 W, (c) 500 W, (d) 1000 W

3.4. Heating and heat preservation performance in different environment temperature

In order to investigate the heating and heat preservation performance of battery pack in different ambient temperature, we simulated the temperature variation of battery pack in -20 ℃, -15 ℃, -10 ℃, -5 ℃, 0 ℃, 5 ℃, 10 ℃, 15 ℃ and 20 ℃. The maximum temperature difference of day and night cycle is 10 ℃. The battery pack successively experiences 5 processes in different ambient temperature: heat preservation – heating – heat preservation – heating – heat preservation. The heating plate setting of case 2 is used and the heating power is 200 W. The Fig.6 shows that the time of each process increases with increasing ambient temperature. The time of 3 heat preservation process and 2 heating process changes a little, as Fig.6 (a) and Fig.6(b) showed, respectively. It indicates that the thermal management shows well stability.

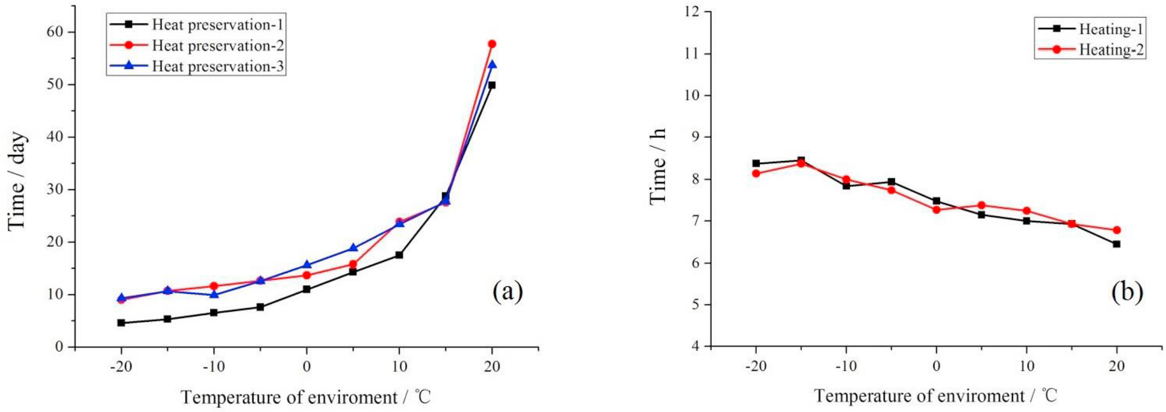

Fig. 6 Time of process versus environment temperature: (a) heat preservation progress, (b) heating process

The Fig.7 shows the maximum temperature difference of batteries in different ambient temperature. The maximum temperature difference of batteries in heat preservation process decreases with increasing ambient temperature and less than 5℃. While, the maximum temperature difference of batteries in heating process changes a little and floats at 3 ℃. The temperature field is influenced by the heating power and heat dissipation power during natural convection. As the heating power is bigger than the heat dissipation power, the temperature difference during the heating process depends on the heating power. When the heating power is same, the temperature difference is similar. When the ambient temperature is unchanged, the temperature difference during 3 heat preservation processes and 2 heating processes change a little. It is benefit to prolong the lifespan of battery.

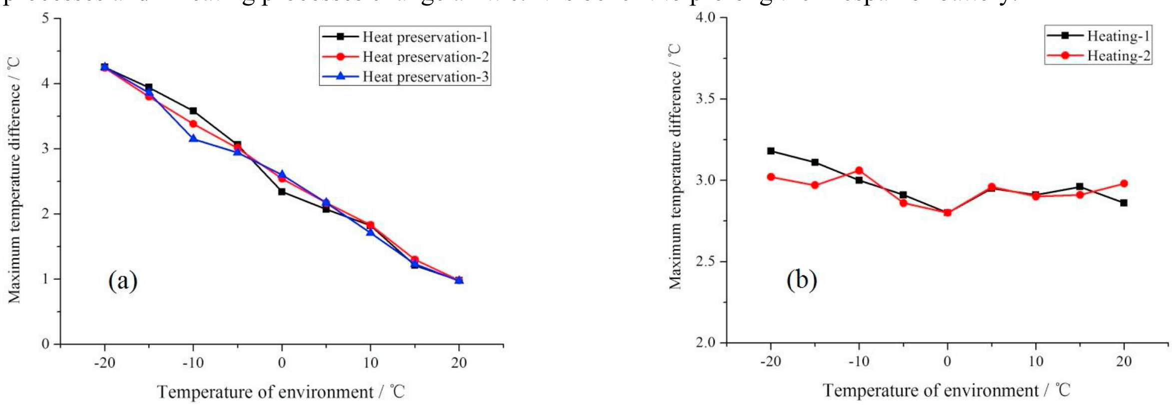

Fig. 7 Maximum temperature difference of battery module versus environment temperature: (a) heat preservation progress, (b) heating process

4. Conclusions

This paper presented the thermal management of 48V Lead-acid battery pack for base station at different temperature based on the heating plate and PCMs. The temperature range of thermal management is confirmed. The effect of area and arrangement of cooling plate on the thermal performance is investigated, as well as the heating power. The heating and heat preservation performance in different environment temperature is researched. At last the performance of pack after continuous heating and heat preservation cycle is simulated to study the stability of this thermal management method. The main results are included:

(1) The combination of heating plate and PCMs can keep the outdoor standby Lead-acid battery pack for base station at optimum temperature range for several days in the cold ambient after once heating process.
(2) When the heating plate is 0.16 m^2, horizontal and under the batteries, compared with other size and arrangements, the temperature uniformity and heat preservation time were improved.
(3) As the heating power increased, the time of heating process and heat preservation process decreased. The optimum heating power is 200 W, which can balance the stability and temperature uniformity.
(4) The time of heating process increases with increasing ambient temperature. And the maximum temperature difference is less than 5℃. In the continuous heating and heat preservation cycle, the time of heating and heat preservation process changes a little. Thermal management performance for outdoor standby battery pack is stable.

5. Acknowledge

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