Performance evaluation of a battery-cooling system using phase-change materials and heat pipes for electric vehicles under the short-circuited battery condition

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Abstract

Electrical vehicles equipped with lithium-ion batteries (LiBs) have been increasing in popularity on the market. LiBs have high energy density and high electric current; however, their lifetimes and performance are known to be strongly influenced by temperature rise due to heat generation, and thermal runaway may occur when the battery temperature exceeds 80 °C. Hence, the development of LiB thermal-management technology is essential. In this study, an A4-sized LiB was short circuited in a prototype cooling system with phase-change material (PCM) and heat pipes (HPs), and the performance of the cooling system was evaluated. To compare the cooling performances, four experimental conditions were adopted: a combination of PCM and HP; PCM only; HP only; and not using the cooling system. In addition, a simulation was conducted under the experimental conditions using a scale model of the cooling system. Thus, we confirmed that the temperature increase of the LiB, especially up to 80 °C, was extended by the effects of PCM. The combination of PCM and HP suppressed the temperature of LiB to be about 80 °C.

Keywords: Lithium-ion battery, Abnormal heat generation, Short circuit, Thermal management technology, Phase change material, Heat pipes

1. Introduction

In recent years, the emissions of greenhouse gases and air pollutants that accompany economic development have become major problems. Economies dependent on fossil fuels for their energy needs in particular are facing serious issues (Poizot and Dolhem, 2011; Hamut et al., 2012). Therefore, it is urgent to develop new energy sources to replace fossil fuels, especially highly efficient renewable energy (Scrosati and Garche, 2010). Recently, electric vehicles (EVs), hybrid electric vehicles, and plug-in hybrid electric vehicles have increased in popularity (Tie and Tan, 2013). Lithium-ion batteries (LiB) are used in these EVs; LiB have high energy density, high power density, and are environmentally friendly; they are widely used as clean-energy sources (Saito, et al. 1997 and Qian, et al. 2016). The International Energy Agency (IEA) reported in 2016 that the number of EVs in the world has reached 2 million. The IEA also predicts that this number will increase rapidly (IEA ed., 2017). However, it is said that the lifetime and performance of LiB are strongly influenced by temperature rise due to heat generation caused by charge, discharge, and the like (Ramadass et al., 2002a, 2002b; Wang et al., 2016; Yuksel et al., 2016). In addition, thermal runaway is caused when the temperature of a LiB exceeds around 80 °C due to short circuiting (Hammami et al., 2003). Gas release, firing, and explosions sometimes accompany such thermal runaway (Lisbona and Snee, 2011; Wang et al., 2012; Pesaran et al., 2013). Therefore, improvement of LiB thermal-management technology is necessary.

Many studies on thermal-management technologies for LiB, such as air- and water-cooling methods, have been performed (Zhang et al., 2009; Fan et al., 2013; Mohammadian and Zhang, 2015). Cooling methods using phase-change materials have also been investigated (Al-Hallaj and Selman, 2000; Khateeb et al., 2005; Javani et al., 2014). Recently, a cooling system combining phase-change materials and mini channels has been developed. Rao et al. designed such a combination system and investigated the influence of fluid-flow rate in the mini channel and thermal conductivity of the phase-change material upon the LiB temperature by simulation. An optimal value of the fluid-flow rate was calculated from this study. Moreover, it was confirmed that the temperature of the LiB can be lowered by increasing the thermal conductivity of the phase-change material (Rao et al., 2016). Xu et al. developed a mini-channel cooling system at battery-module level and numerically simulated it with a nail-penetration model. It was found that the propagation of thermal runaway from one LiB to the adjacent one can be prevented by a mini-channel cooling system capable of independently controlling the coolant-flow rate for each LiB (Xu et al., 2017).

In spite of these studies, fire accidents in LiB-powered EVs and aircraft due to LiB breakdown or accidents have been reported in the past 10 years (Feng et al., 2017). Many of these fire accidents are thought to have occurred as a result of short circuiting and thermal runaway of the LiB. In addition, if any accidents occur and the power necessary for cooling by water or forced air cannot be obtained, a sufficient cooling effect may not be secured. We believe that it is necessary to establish a technology that can cool LiB even in such severe cases.

The authors have previously developed a prototype hybrid-type cooling system using heat pipes (HP) and phase-change material (PCM), and examined the cooling performance of this system (Yamada et al. al., 2017). In this study, one LiB incorporated into the cooling system was actually short-circuited and its cooling performance was verified. In order to compare the cooling performance, experiments were conducted under four experimental conditions: cooling using a combination of PCM and HP, cooling using PCM only, cooling using HP only, and without using cooling system. Moreover, heat-transfer calculations were performed under experimental conditions using the same scale model as the cooling system and the system's thermal behavior was analyzed by comparing both results.

2. Experimental device and method

2.1 Preliminary experiment

In evaluating the performance of this cooling system, it was necessary to determine how long the temperature rise of the LiB should be suppressed. For this reason, a preliminary experiment in which a single LiB cell was externally short-circuited was conducted. The external short circuit was made in a thermostatic chamber with a single LiB connected to the magnetic contactor via conducting wires. The magnetic contactor was made by Fuji Electric FA Components & Systems Co., Ltd. (SB-N2 type), and the conducting wires were made by Mitsuboshi Co., Ltd. (2PNCT type, cross section: 60 mm²). The time of the external short circuit could be arbitrarily set by opening and closing the switch inside the magnetic contactor. For the preliminary experiment, a laminate-type LiB (size: 237 mm × 201 mm × 8.5 mm, nominal capacity: 22 Ah, cathode: lithium iron phosphate (LiFePO₄), anode: graphite) was used. A schematic view of preliminary experiment is shown in Fig. 1. The temperature-measurement positions of LiB were set on the surface near the anode and near the center, respectively. The LiB-temperature results shown in this paper are the highest values of these two positions. K-type sheath thermocouples were used for temperature measurement and GRAPHTEC GL820 was used as a data logger. Temperature changes were recorded at 0.1 second intervals. A program-logic controller (PLC) was used to control the switch opening / closing of the magnetic contactor.

Fig. 1 Schematic view of the preliminary experiment in the thermostatic chamber.

Changes in the temperature and heat generation of the LiB in the preliminary experiment are shown in Fig. 2. The LiB temperature sharply increased immediately after the start of the short circuit and reached 80 °C within about 20 seconds. Although temperature temporarily decreased afterward, the maximum temperature reached 116.7 °C after 186 seconds. Despite the LiB temperature decreasing slowly after reaching its maximum, heat generation had already decreased greatly when the maximum temperature was reached. Heat generation was calculated using Eq. (1) based on the temporal change of the battery temperature obtained in the experiment,

$$Q = mc\Delta T \quad (1)$$

Here, Q [W] is the heat-generation of the battery, m [kg] is the battery mass, c [J/(kg·K)] is the specific heat of the battery, and ΔT [°C/s] is the temperature difference per unit time. From this result, the initial peak of heat generation itself was considered to have little influence upon thermal runaway of the LiB after a certain time passed. Therefore, it was important to determine how LiB-temperature rise can be suppressed up to 200 seconds after short circuiting commences. Accordingly, for subsequent experiments and simulations, the results up to 200 seconds after the start of short circuiting were investigated. In this preliminary experiment, there was no constraint on the shape of the LiB cell, and the LiB was short-circuited after putting it on a plate. Therefore, about 40 seconds after starting LiB short circuiting (when LiB temperature reached about 90 °C), expansion of the LiB started and its thickness finally reached 5 to 6 times the initial value. This result is shown in Fig. 3.

Fig. 2 Change of LiB temperature and heat generation in the preliminary experiment.

Fig. 3 Expansion of the LiB (a) After preliminary experiment, (b) Before the preliminary experiment.

2.2 The cooling system

From the preliminary experimental results, the temperature of the LiB was found to peak about 200 seconds after short circuiting started and the cooling performance up to this time was very important. Therefore, in this study, using the hybrid cooling system with PCM and HP devised by Yamada et al., the cooling performance to that time was mainly investigated. For this cooling system, the cooling performance at a heat generation of 400 W was reported (Yamada et al., 2017). This cooling system is shown in Fig. 4; the cooling system was constituted for a battery module in which four LiB were arranged in parallel (Fig.4 (b)). Twenty HPs were installed on each side of the battery module so that forty HPs were in contact with the LiB. HP had ten fins at a 7.5 mm interval on each side, twenty fins in total. PCM filled the gap between the LiB, HP, and container. The heat flow of this cooling system is shown schematically in Fig. 5. Heat generated from the LiB was transported to the PCM and HP, respectively. Part of the heat transferred to the PCM was stored as latent heat and the other heat moved to the HP and then was released to the outside air through the fins.

LiB cells, which were the same as in the preliminary experiment, were loaded into the system. HP was made of copper (flat part: 120 mm × 10 mm × 3 mm, cylindrical part: 100 mm × φ 8 mm) and the working fluid in HP was pure water (Fig.4 (c)). The basic shape of HP used in the cooling system was cylindrical shape with diameter of 8 mm, which was later compressed to have flat portion of 3 mm thickness. The fin was made of aluminum (size: 230 mm × 119 mm ×

0.3 mm), the container was made of polyvinyl chloride (size: 200 mm × 49 mm × 220 mm). RT50 (melting point: 45 to 51 °C, thermal conductivity: 0.2 W/(m·K)) made by Rubitherm Technologies GmbH (company of Germany) was used as a PCM. Thermal runaway occurs at LiB internal temperatures above about 80 °C; therefore, it is necessary to suppress the temperature of the LiB below 80 °C within 200 seconds after short circuiting commences. To effectively suppress LiB temperature using the latent heat of PCM, RT50 with a melting point below the actual thermal-management-target temperature of 50 °C was selected.

Fig. 4 The cooling system (a) Over view, (b) Schematic view, (c) Heat pipes with fins.

Fig. 5 Heat flow of the cooling system. (a) From LiB to PCM and HP; (b) From PCM to HP; (c) From HP to Fin; (d) From Fin to Air.

2.3 Experimental method

In this experiment, it was assumed that one of four LiB in the device suddenly increased in temperature due to abnormal heat generation, and the cooling performance of the system at that time was verified. One LiB in the center of the cooling device was externally short circuited. One LiB with a state of charge (SoC) of 100% and three with SoCs of 0% were used in. SoC is the ratio of the amount of electricity charged to the electric capacity of the battery. As in the preliminary experiment, external short circuiting was done by connecting one LiB to the magnetic contactor. The state of the constructed circuit is shown in Fig. 6. In the preliminary experiment, as shown in Fig. 3, expansion started at the time when the LiB-surface temperature reached 90 °C and finally the LiB thickness became 5 to 6 times its initial value. In LiB short circuit experiments using the cooling system, LiB expanded and the whole cooling system could be broken. Therefore, for safety reasons, the experiment was terminated when the LiB temperature reached approximately 90 °C under all conditions.

In addition to experimentation using the cooling system, three other experiments were conducted for comparison. Experimental conditions were (1)-(4) below:

- (1) Cooling with both PCM and HP: the cooling system shown in Fig. 4. (PCM & HP);
- (2) Cooling with PCM only: a state in which only RT50 was incorporated in the cooling system. (PCM only);
- (3) Cooling with HP only: a state in which only HP was incorporated in the cooling system; since RT 50 was not incorporated, LiB was in contact with air. (HP only);
- (4) Natural air cooling: neither RT 50 nor HP were used; since the LiB cells cannot stand by themselves without

RT50 or HP, spacers (size: 240 mm × 8 mm × 2 mm, made of acrylic) were inserted between LiB (without cooling).

The measurement positions of the LiB temperature and loading position of the LiB to be externally short-circuited in the experiment are shown in Fig. 7. The temperature-measurement positions of the LiB were set in the vicinity of the negative electrode and the central point on the surface of the LiB, respectively. In the preliminary experiment, the temperature in the vicinity of the negative electrode of LiB was that temperature rising was the fastest when LiB was short-circuited and the temperature in the center of LiB was the highest temperature in short circuit. The results shown in the following figures correspond to the highest temperature among these two positions, although the difference between the two was only a few degrees. As in the preliminary experiment, K-type sheath thermocouples were used for temperature measurement and GRAPHTEC GL820 was used as a data logger. Temperature changes were recorded at 2 second intervals.

Fig. 6 Experimental equipment in the thermostatic chamber (a) Photo, (b) Schematic view.

Fig. 7 Position of the LiB to be short circuited and measurement points in the experiment (a) Front view, (b) Side view.

3. Numerical model and calculation condition

3.1 Numerical model

In order to evaluate the performance of the cooling system, ANSYS Fluent Ver. 17.0 (CFD software) was used and thermal conduction was mainly calculated. Numerical models used in this calculation are shown in Figs. 8 and 9. These models have the same dimensions and arrangement of parts as the experimental setup. Two sets of numerical models were used, one with HP and one without. The mesh data for this calculation are shown in Tables 1 and 2, respectively.

The measurement positions of LiB temperature in this calculation are shown in Fig. 10. In this calculation, it was found that the increasing behavior of LiB temperature differed from that in the experiment. Therefore, it was at first unknown which point of LiB would indicate the highest temperature; thus, three points were added to the measurement points of the temperature in the calculation.

Fig. 8 Numerical model with HP (a) Over view, (b) Cross section, (c) Meshes of the model.

Fig. 9 Numerical model without HP (a) Over view, (b) Cross section, (c) Meshes of the model.

Table 1 Mesh data (With HP model).

Minimum mesh size [mm]	1.0
Maximum mesh size [mm]	2.0
Shape of mesh	Hexahedron
Number of element	977,035

Table 2 Mesh data (Without HP model).

Minimum mesh size [mm]	1.0
Maximum mesh size [mm]	2.0
Shape of mesh	Hexahedron
Number of element	446,600

Fig. 10 Sizes of the LiB cell to be short circuited and measurement points in the calculation.

3.2 Physical properties, boundary condition, and calculation condition

Physical property values used in this numerical model are shown in Tables 3 to 7. The heat-transfer coefficients of the fin, PCM, and container surfaces are shown in Table 8. The property values for copper, polyvinyl chloride, aluminum, and PCM (RT50) at 25.0 °C were used for the HP, container, fins, and PCM, respectively. The value of the effective thermal conductivity of the HP was set to 30 times larger than the thermal conductivity of copper (398 W/(m·K)). As the physical-property values of the LiB, the estimated values provided by Uzushio Electric Co., Ltd. were used.

Table 3 Physical properties of LiB.

Density [kg/m ³]	2179
Specific heat [J/(kg · K)]	1016.4
Thermal conductivity [W/(m · K)]	8

Table 5 Physical properties of fins.

Density [kg/m ³]	2719
Specific heat [J/(kg · K)]	871
Thermal conductivity [W/(m · K)]	202.4

Table 7 Physical properties of PCM.

Density (at 322K) [kg/m ³]	880
Density (at 353K) [kg/m ³]	760
Specific heat [J/(kg · K)]	2000
Thermal conductivity [W/(m · K)]	0.2
Viscosity [kg/(m · s)]	0.0237
Pure solvent melting heat [kJ/kg]	160
Solids temperature [K]	322.15
Liquids temperature [K]	322.15

Table 4 Physical properties of heat pipes.

Density [kg/m ³]	2857
Specific heat [J/(kg · K)]	381
Thermal conductivity [W/(m · K)]	11940

Table 6 Physical properties of container
(Polyvinyl chloride).

Density [kg/m ³]	1450
Specific heat [J/(kg · K)]	1000
Thermal conductivity [W/(m · K)]	0.167

Table 8 Boundary conditions
(Heat-transfer coefficients).

Cooler of fin [W/(m ² · K)]	5.0
Top of PCM [W/(m ² · K)]	4.0
Outer of case [W/(m ² · K)]	4.0

There are contact thermal resistances on the boundary surfaces of the LiB, HP, PCM, and the like. Therefore, calculation was performed to estimate contact thermal resistance. According to Fourier's law, the heat-flux equation is Eq. (2), from which we obtain Eq. (3),

$$q = k \frac{\Delta T}{l} \quad (2)$$

$$q = \frac{\Delta T}{(l/k)} \quad (3)$$

Here, q [W/m²] is the heat flux passing through an object, k [W/(m·K)] is the thermal conductivity of the object, ΔT [K] is the temperature difference in the object, and l [m] is the object's thickness. The denominator l/k of equation (2) is defined as the object's thermal resistance. In ANSYS Fluent, contact-thermal resistance can be set by applying this value to the boundary surface between any objects. In this case, l is the imaginary thickness of the boundary interface and k is the thermal conductivity of the boundary substance. Here, the contact-thermal resistance of the boundary surface was set and calculation was done as described above. In this calculation, a thermal conductivity of 0.2 W/(m·K) was set as the value for the virtual thickness substance. This is the same value as the thermal conductivity of the PCM used in the experiment. The contact-thermal-resistance values used in the calculation are shown in Table 9.

Table 9 Contact-thermal resistance (Using a PCM model).

Interface between two objects	Wall thickness [mm]	Value [(m ² ·K)/W]
LiB — Heat Pipe	0.3	0.0015
LiB — PCM	1.2	0.006
HP — PCM	0.1	0.0005
PCM — Container	0.4	0.002

The numerical calculation was performed in the case where LiB was externally short circuited to represent abnormal heat generation corresponding to the experiment by giving a large heat generation to one of the four LiB. In the simulation of the PCM material, the thermal conduction and solid-liquid phase change were considered. The convection of melted PCM was neglected for simplicity.

3.3 Heat generation setup

In ANSYS Fluent, users can customize various conditions necessary for calculation by setting user-defined functions. In this calculation, some user-defined functions were used as source terms. When using user-defined functions, it is necessary to set mathematical-function expressions.

For calculation of experiment using PCM, independently set mathematical functions were used as the heat-generation source. Graphs comparing the functions of heat generation and its temporal change in the LiB in the preliminary experiment are shown in Fig. 11. As can be seen from Fig. 11, the temporal change in the heat generation obtained from the preliminary experiment was found to be very complicated. At first, the temporal-change equation of heat generation, which reproduced these data faithfully, was used in the calculation. In the preliminary experiment, the temperature was measured in open atmosphere without constraint on the LiB shape; then, the heat generation was estimated from the measured data. However, in this short circuit experiment, LiB cells were inserted into a container holding heat-absorbing parts such as PCM and HP. Therefore, the temperature change in this experiment was not successfully reproduced, even if the temporal change of heat generation obtained from the preliminary experiment was used. Thus, temperature-change equations adjusted to the short circuit experiment were necessary. The following functions were obtained by considering the tendency in the preliminary experiment and by adjusting them to reproduce the temperature obtained in the short-circuit experiment (in this case, with PCM only and PCM & HP). These functions were divided into two parts, from zero to 30 seconds from the start of short circuiting and after 30 seconds, and are respectively shown as Eqs. (4) and (5):

$$S = \frac{500000}{0.002t + 0.12} - 250000 \quad (0 [s] < t < 30 [s]) \quad (4)$$

$$S = \frac{250000}{0.00096t + 0.12} - 50000 \quad (30 [s] < t) \quad (5)$$

Here, S [W/m³] is the heat generation per unit volume and t [sec] is the elapsed time. Since these are dictated for Fluent, heat generation is the value per unit volume. A plot of these functional expressions is also shown in Fig. 11. Although there is some difference between the two plots, as we stated, this is a result of adjustments to reproduce the experimentally measured temperature in the container.

Fig. 11 Temporal change data of LiB heat generation in the preliminary experiment and the adjusted function for calculation.

4. Results and discussions

4.1 Experimental results

The time series of LiB-temperature rise from the start of short circuiting under each condition are shown in Fig. 12. At 30 seconds under the “HP only” and “without cooling” conditions, the maximum temperatures of LiB became 91.3 °C

and 89.9 °C, respectively. Therefore, the experiment was stopped at this point for safety reasons. At this time, in the “PCM & HP” and “PCM only” cases, the temperatures of the LiB were 55.0 °C and 60.2 °C, respectively. The cooling effects by HP only and without cooling were confirmed to be insufficient under extremely large heat generation due to external short circuiting. On the other hand, for PCM & HP and PCM only, it was confirmed that the maximum temperature of the LiB up to 30 seconds from the start could be suppressed to about 60 °C. From this reason, cooling by PCM can be said to be effective for preventing sudden temperature rise in the initial stage of short circuiting the LiB.

The results of the temperature change of LiB when LiB was short-circuited for a long time in the “PCM & HP” and “PCM only” cases are shown in Table 10. Moreover, the time until the temperature of LiB reached 80 °C is shown in Table 11 and the maximum temperature of the LiB is shown in Table 12. Using only PCM, LiB temperature reached 80 °C in 88 seconds after starting to short circuit and reached a maximum temperature of 92.5 °C in 200 seconds. In PCM & HP, LiB temperature reached 80 °C in 178 seconds after short circuiting started and reached a maximum temperature of 80.1 °C in 182 seconds. Therefore, in the case of PCM & HP, the time until the LiB temperature reached 80 °C was about two times longer than when using PCM only, and the maximum temperature was reduced by about 10 °C. Moreover, comparing the temperature change between PCM & HP and PCM only, temperature changes differed from about 30 seconds after starting short circuit and the temperature difference became noticeable at 50 to 100 seconds. The cooling effect by HP and the fins began to appear at that time. As a result, the maximum temperature of the LiB was suppressed to about 80 °C. It is consider the temperature of the LiB to become dangerous at about 80 °C (Yamada et al., 2017), and from this experimental result, it can be said that the prototype cooling system prevented temperature from becoming dangerous during short circuiting for a long time. Thus it was confirmed that the combination of PCM and HP is effective for preventing rapid temperature rise of the LiB, experimentally.

Fig. 12 Comparison of LiB temperature under four experimental conditions, with 80 °C (red) and 90 °C (black) lines overlaid.

Table 10 Temporal change of LiB temperature in experiment.

Time [s]	Temperature [°C]	
	PCM	PCM&HP
0	27.1	26.7
10	42.2	39.3
20	52.8	51.9
30	60.2	55.0
50	70.7	64.4
100	82.6	75.0
150	90.6	79.0
200	92.5	80.0

Table 11 Time until reaching 80°C.

	HP	Without Cooling	PCM only	PCM&HP
Time [s]	17	19	88	178

Table 12 Maximum temperature of the LiB using PCM&HP and PCM only.

	PCM only	PCM&HP
Temperature [°C]	92.5	80.1

4.2 Calculation results

4.2.1 Comparison with experimental results

Our experimental results confirm that "PCM & HP" and "PCM only," among the experimental conditions used in this study, were effective against rapid temperature rise of the LiB. Therefore, the temperature change of the LiB was simulated only in the two models corresponding to PCM & HP and PCM only, with Eqs. (3) and (4) used to model heat generation in the LiB. To analyze the calculation results, the temperature at the position of the lowest height among the five measurement positions in Fig. 10 was adopted, as the temperature at this position indicated the highest value in the calculation, which will be shown later in Figs. 17 (b), (c) and (d). This could be thought reasonable due to the difference in the manner of heating between the experiment and the simulation. In the experiment, the heating distribution was determined by the inner-current distribution, whereas in the calculation, the heat generation was uniformly given to the whole volume since the current distribution was difficult to predict. In this study, we discuss the maximum temperature of the LiB. Therefore, we simply adopted the highest temperature in the LiB regardless of its position. Calculation and experimental results are compared in Fig. 13 and Table 13, respectively. Moreover, the time needed for the temperature of the LiB to reach 80 °C and the maximum temperature of the LiB are shown in Tables 14 and 15, respectively. As can be seen from Fig. 13, in PCM & HP, the temperature changes of the LiB in the calculation and the experiment tended to be very similar. Similar results were obtained for PCM only too. For this reason, it can be said that results consistent with experimental values were reproduced by Eqs. (3) and (4) for heat generation by the LiB and by adjusting them with numerical models. Also, since both cases of PCM & HP and PCM only were loaded with PCM, the temperature rise of the LiB was suppressed in the case of PCM & HP because the heat generated by the LiB was released outside by the HP.

Fig. 13 Comparison of LiB temperature between experiments and calculations.

Table 13 Temporal change of LiB temperature in experiments and calculations.

Time [s]	Temperature [°C]			
	PCM only		PCM+HP	
	Experiment	Calculation	Experiment	Calculation
0	27.1	25.0	26.7	25.0
50	70.7	70.7	64.4	67.2
100	82.6	82.7	75.0	76.6
150	90.6	86.9	79.0	80.0
200	92.5	90.4	80.0	80.4

Table 14 Time until reaching 80°C.

	PCM only		PCM&HP	
	Expt.	Calc.	Expt.	Calc.
Time [s]	88	83	178	151

Table 15 Maximum temperature of the LiB.

	PCM only		PCM&HP	
	Expt.	Calc.	Expt.	Calc.
Temperature [°C]	92.8	92.5	80.1	80.5

4.2.2 Effect of PCM

We here state the details of the effect of PCM in the cooling system during external short circuiting of a LiB. The calculation results of the temperature changes of the LiB, PCM, HP, and fin in the PCM & HP model, and of the LiB and PCM in the PCM only model, are shown in Fig. 14 and Table 16, respectively. The representative temperatures in Fig. 14 and Table 16 were collected and adopted at the following positions, respectively, because we wanted our comparisons to be clear and meaningful. In the PCM & HP model, the temperatures of the LiB and PCM were at the lowest height among the five measurement positions in Fig. 10. The temperature of the HP was measured at the heat pipe in contact with the highest position of the LiB, and that of the fin was at the fin plate closest to the cooling device and on its center line in the plate area. In the PCM only model, the temperatures of the LiB and PCM were at the center of the LiB.

In both the PCM & HP and PCM only models, the temperature of the LiB sharply increased immediately after short circuiting started. Then, it can be seen that the temperature rise of the PCM occurred earlier than that of the HP or fins in the PCM & HP case. It is thought that the heat released from the LiB moved to PCM rather than HP immediately after short circuiting. In addition, since the temperature rise of the HP and fins was small, the temperature difference between the fins and the outside air was also small and so too was the amount of heat released to the outside air.

The amounts of heat transferred from the LiB to the HP and from the LiB to the PCM in the PCM & HP model, the sum of these values, and the amounts of heat transferred from the LiB to the PCM in the PCM only model are shown in Fig. 15. The data of amounts of heat transferred were directly obtained from the calculation results of ANSYS Fluent. From Fig. 15, it can be seen that the amount of heat transferred from the LiB to the PCM immediately after short circuiting started was larger than that transferred from the LiB to the HP in the PCM & HP case, due to the differences in contact area between the LiB and the HP and PCM. The LiB-PCM contact area was about four times larger than the LiB-HP one. Therefore, the amount of heat transferred from the LiB to the PCM was larger. The amount of heat transferred from the LiB to the HP after 50 seconds of short circuiting exceeded that transferred from the LiB to the PCM since heat transport by the HP increased. Moreover, as shown in Figs. 13 and 14, although the amount of heat transferred from the LiB to the PCM in the PCM only case was larger than that in the PCM & HP case, the tendencies of PCM temperature and temperature change were almost the same under both conditions. In both cases, when the PCM reached the melting point, the temperature was effectively kept at this point. Thus, there was hardly any difference in PCM temperature at the point where data was taken. Also, from Fig. 15, it is seen that in PCM & HP, after a certain time had elapsed from the start of short circuiting the LiB, the heat generation of the LiB moved to HP rather than to PCM. Therefore, it took some time for the heat transfer to the HP to increase, and it can be said that cooling by the PCM is more effective than by the HP at the initial stage of short circuiting.

Fig. 14 Comparison of the LiB, PCM, HP and Fin temperatures between the PCM&HP and PCM only model.

Table 16 Temporal change of LiB, PCM, HP and Fin temperature in the PCM&HP and PCM only models.

Time [s]	Temperature [°C]					
	PCM&HP model				PCM only model	
	LiB	PCM	HP	Fin	LiB	PCM
0	25.0	25.0	25.0	25.0	25.0	25.0
10	40.3	29.2	27.7	26.4	40.4	28.9
20	51.8	35.4	31.3	28.7	52.4	34.7
30	60.7	41.3	34.5	30.8	62.1	40.6
50	67.2	49.0	38.2	33.5	70.7	49.0
100	76.6	49.5	43.1	37.4	82.7	49.1

Fig. 15 Amount of heat transferred from the LiB to the HP or PCM in the PCM&HP and PCM only models.

4.2.3 Effects of HP

Here, we look at the effect of HP in the cooling system under external short circuiting of a LiB. From Table 12, it was confirmed that the time required for the maximum temperature of the LiB to reach 80 °C in the experiment with PCM & HP was 178 seconds, about twice as long as the 88 seconds needed in the PCM only case. Temperature distributions at 50 seconds, 100 seconds, 150 seconds and 200 seconds after the start of short circuiting in the XY section of the module in the PCM & HP and PCM only models are shown in Figs. 17 and 18, respectively. The XY cross section was set to a position passing through the middle position of the thickness of the heated LiB. The XY section is shown in Fig. 16(a). As shown in Figs. 17 and 18, in the PCM & HP models, there was some temperature difference between the part where the HP contacted the LiB and the part where it was not in contact with the LiB. On the contrary, in the PCM only case, there was a uniform temperature difference from the center of LiB to the outside. The temperature difference at this contact point started to be seen 50 seconds after short circuiting started, although the figure at less than 50 seconds is not shown here, and it became remarkable after 150 seconds. From this result, it can be said that the cooling effect by HP began to appear at about 50 seconds from the start of short circuiting. In addition, Fig. 15 shows that the total values of the heat transferred from the LiB to the PCM and to the HP in the PCM & HP model exceeded that transferred from the LiB to the PCM in the PCM only case (as can be understood from Figs. 17 and 18) due to cooling effect of the HP. This may explain why the time until the LiB temperature reached 80 °C in the PCM & HP case was extended over the PCM only case.

The temperature distributions at 50 seconds, 100 seconds, 150 seconds and 200 seconds of short circuiting in the ZX cross section of the module center in the PCM & HP and PCM only models are shown in Figs. 19 and 20, respectively. The ZX cross section was set at a position passing through the middle of the height direction of the cooling system. The ZX cross section is shown in Fig. 16(b). From these results, it is seen that the heat moved faster throughout the module

in the container in the PCM & HP case than in the PCM only case. This was because the heat transferred from the heated LiB was released from the fins and simultaneously passed through the adjacent HP through the fins to again move into the module and transfer into the adjacent LiB and its surrounding PCM. This is an interesting side effect of this HP system and may lead to effective use of the latent heat of the whole PCM inside the container. Thus, it can be said that the HP was performing effectively about 50 seconds after short circuiting started.

Fig. 16 Cross sections for the temperature distribution of each model (a) XY cross section, (b) ZX cross section.

Fig. 17 Temperature distribution at XY cross section of the PCM&HP model at (a) 50 s, (b) 100 s, (c) 150 s and (d) 200 s.

Fig. 18 Temperature distribution at XY cross section of the PCM only model at (a) 50 s, (b) 100 s, (c) 150 s and (d) 200 s.

Fig. 19 Temperature distribution at ZX cross section of the PCM&HP model (a) 50 s, (b) 100 s, (c) 150 s and (d) 200 s.

Fig. 20 Temperature distribution at ZX cross section of the PCM only model (a) 50 s, (b) 100 s, (c) 150 s and (d) 200 s.

4.2.4 Melting situation of PCM

We here describe the PCM's melting situation during external short circuiting of the LiB. The temporal change of the PCM's melting rate in the PCM & HP and PCM only models up to 200 seconds are shown in Fig. 21. The melting rate means the volumetric ratio of the melted amount of PCM to the total PCM volume. Comparing the melting rates under the two cases, that of the PCM & HP case was larger. As shown in Figs. 19 and 20, the PCM-melting rate was thought to be higher in the PCM & HP case than in the PCM only case because the heat released from LiB was transferred to the entire inside of the module more quickly for the former case.

The maximum PCM-melting rates at 200 seconds in the PCM & HP and PCM only cases are shown in Table 17, respectively. In both cases, the maximum PCM-melting rate was less than 15%. This was because the heat generation by the LiB decreased with the passage of time, and then there was insufficient heat to melt the whole PCM. Thus, there remains room for improvement in PCM-loading capacity and loading methods in the system in order to make more effective use of the latent heat of fusion of the PCM.

Fig. 21 Change of the volumetric ratio of melted PCM in the PCM&HP and PCM only model until 200 s.

Table 17 Maximum volumetric ratio of melted PCM to total PCM volume in the PCM&HP and PCM only models.

	PCM only	PCM&HP
Maximum volumetric ratio of melted PCM [%]	11.5	13.4

5. Conclusion

In this study, experiments and calculations were conducted on the cooling system devised and prototyped by Yamada et al. and the cooling performance under a rapid temperature rise when one LiB was externally short circuited was evaluated and verified. The following conclusions were confirmed.

- 1) It was found that LiB-temperature rise in the initial stage of short circuiting was suppressed more using PCM than without PCM. In particular, when PCM and HP were combined, the time until the temperature of the LiB reached 80 °C was 178 seconds, and the LiB's temperature remained at around this value.
- 2) In the system with combined PCM and HP, it was thought from the calculation results that the heat generated from the LiB at the initial stage of short circuiting moved to the PCM rather than to the HP, and the LiB was cooled by the PCM's latent heat. It was confirmed that after about 50 seconds of short circuiting, the heat transported to HP became active and the cooling performance began to be promoted.
- 3) From the calculation results, it was confirmed that the melted PCM was less than 15% of the total amount of PCM loaded in the system in both the PCM only and PCM & HP cases. It is thought that there remains room for improvement for effective utilization of the PCM.

It was found that the LiB-cooling system consisting of a combination of PCM and HP used in this study can keep the temperature of the LiB at about 80 °C or less, even during long-term short circuiting of one LiB cell. Therefore, this cooling performance seems to be effective against most situations that may actually be encountered. However, only about 15% of the PCM loaded in the cooling system was melted after 200 seconds of short circuiting, as shown by the calculation. Therefore, the latent heat of the PCM that did not melt was not effectively employed. It is thought that this is because the number of HP in this system, the loading capacity of the PCM, and the melting point were not well-optimized. Therefore, it is possible that the temperature rise of the LiB can be further suppressed by optimization. Further experiments and calculations will be conducted in the future and it is necessary to determine the number of HP, the loading capacity of the PCM, and the optimum melting point of the PCM.

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