1. Introduction

Everyday life has changed dramatically and improved rapidly since the 18th century owing to the use of fossil fuels. Although energy technologies have proven essential for global prosperity, too much use of fossil fuels is causing serious problems for the human race (Poizot and Dolhem, 2011). Substances discharged when fossil fuels are consumed, such as CO$_2$, NO$_x$, and SO$_x$ are global warming gases, and air pollutants. The amount of CO$_2$ discharged in 2005 was almost double that in 1970 (Scrosati and Garche, 2010). As a result, clean and renewable energy sources and efficient energy use have both become necessary in our daily lives as well as in various industries and transportation systems. In recent years, electric vehicles (EVs), hybrid electric vehicles (HVs), and plug-in hybrid electric vehicles (PHVs) have been developed; these vehicles are generally known as EVs. To achieve high energy efficiency, these cars often use a lithium-ion battery (LiB) as a secondary battery. Owing to the sophistication of anode and cathode materials, LiBs have been adapted for small electronic equipment such as personal computers (PC) and smart phones as well as EVs. Improvements in the energy and power densities of secondary batteries like LiBs have been attempted, and a road-map has been proposed (New Energy and Industrial Technology Development Organization, 2013). However, LiBs generate a lot of heat during charging and discharging, which leads to a severe deterioration in their electrical performance. Recently, a number of studies (Ramadass et al., 2002a, 2002b; Wang et al., 2012) have reported on fires and explosions occurring in EVs equipped with LiBs; it is thought that thermal runaway caused these problems.

Generally, when an exothermic reaction advances too much, the temperature soars and the reaction is accelerated due to a temperature increase (Mandal et al., 2006; Sponitz et al., 2007). In the case of LiBs, it is reported that severe
damage is done to their internal structure when they reach 80 °C–85 °C (Hammami et al., 2003). These problems must be solved to improve the safety of EVs; therefore, it is necessary to determine what heat control technologies could be used.

In this study, we aimed to mitigate thermal runaway by developing a prototype of a hybrid cooling system that combines phase-change materials (PCM) and heat pipes to control abnormal heat emissions from an LiB. This prototype system is intended for A4-sized laminated-type LiBs built with a paraffin wax PCM and heat pipes. We conducted experiments using this system at temperatures that would generally result in thermal runaway. Moreover, we performed a numerical analysis of the heat balance and thermal distribution during abnormal heating. With the help of the calculation results, the thermal behavior in the experimental system was studied and the effect of the heat pipes and PCM were discussed.

2. Lithium-ion battery hybrid-cooling system

2.1 Lithium-ion battery

LiBs are a type of secondary batteries that use graphite as the cathode and, for example, lithium-cobalt oxide (LiCoO₂), lithium-manganese oxide (LiMn₂O₄), or lithium iron phosphate (LiFePO₄) as the anode. As such, these systems have a simple structure, high electrical conductivity and no memory effect, which means that the LiBs can be lightweight, small, and have high energy density. Recently, LiBs have been adapted for small electronic equipment such as personal computers and smartphones. LiBs, however, have quite poor thermal stability and, therefore, should be kept at around 15 °C–45 °C. It has been pointed out that if the appropriate temperature is not maintained, the life cycle of an LiB will shorten. Excessive charging and discharging has also been found to be another factor causing abnormal heating that leads to thermal runaway (Johnson and White, 1998; Vetter et al., 2005; Horie, 2010; Rao and Wang, 2011).

To sustain the practical performance of LiBs, a cooling system would need to be used that could keep the battery at a suitable temperature range, but it would also need to be small, lightweight, have a simple structure, be low cost, and easy to maintain (Pesaran et al., 1999; Yang et al., 2006; Rao and Wang, 2011).

Four methods have been proposed as heat control techniques for LiBs used as EV power sources (Rao and Wang, 2011); namely, (1) air cooling, (2) liquid cooling (including heat pipes), (3) use of PCMs, and (4) a combination of the three aforementioned methods (Rao and Wang, 2011).

Air cooling devices, especially natural cooling devices, have quite a simple structure, are inexpensive, small, and easy to maintain; this is why they have been extensively studied (Jung et al., 2002; Mahamud and Park, 2011; Nelson et al., 2002; Wu et al., 2002; Zolot et al., 2002; Rao and Wang, 2011).

Forced air cooling (or liquid cooling) devices can readily maintain a suitable operating temperature range; however, as some accessories such as blowers, fans, or pumps, need to be contained within the whole system, it would need a more complex structure, would be more expensive, and would be larger than desired. Furthermore, measures would...
need to be implemented to avoid coolant leaks (Pendergast et al., 2011; Rao and Wang, 2011).

Heat pipes (HPs) are spontaneously operated small elements that utilize phase-change heat transfer. These pipes can transport large amounts of heat energy using very small temperature differences. Their structure comprises only an airtight container and a working fluid. When one side of the container is heated and the other is cooled, a vapor phase occurs in the heating area and moves to the cooling area, where it turns into a liquid phase. This liquid is returned to the heating area by a capillary force. The above-mentioned cycle enables continuous heat transport (Panigrahi, 2016). There are various types of such airtight containers, such as ones having a circular cross-section, a rectangular cross-section, and a loop type (Japan Heatpipe Association, 2001). There are numerous examples of LiB cooling equipment using heat pipes; these have adopted straight-line heat pipes, loop-type thermosiphons, and pulsation heat pipes (PHPs), but these are in the fundamental research stage (Jang and Rhi, 2010; Rao et al., 2013; Hong et al., 2015).

2.2 Phase change material

PCMs are heat-storage materials that utilize latent heat. They can charge or discharge this heat energy by changing the phase. PCMs are classified by their composition, e.g., organic, inorganic, or eutectic (Sharma et al., 2009; Rao and Wang, 2011). The criteria for selecting a PCM as an LiB heat control device are that (1) it has high latent heat, specific heat, and thermal conductivity, (2) small volume change, (3) no supercooling, (4) is not toxic, (5) is not a fire hazard, and (6) is inexpensive. A material that satisfies most of these criteria is paraffin wax, an organic PCM. Paraffin wax mostly comprises a mixture of straight chain n-alkanes, CH$_3$–(CH$_2$)$_n$–CH$_3$. The melting point, or latent heat of fusion, of paraffin wax can be varied by varying the chain length, which allows it to operate at a large temperature range (Sharma et al., 2009; Rao and Wang, 2011). Al-Hallaj et al. conducted a series of experimental and numerical studies on a thermal management system for LiBs in EVs that used paraffin wax as the LiB heat control device. They found that an appropriate operating temperature range for the LiB could be maintained by the PCM (Al-Hallaj and Selman, 2000; Khateeb et al., 2005; Mills and Al-Hallaj, 2005; Kizilel et al., 2008).

2.3 Building of the prototype cooling system

In this study, we built a prototype of a hybrid cooling system that combined a paraffin PCM and heat pipes; this system was used as a thermal control device for the abnormal heating of an LiB in an EV. An abnormal heat emission is predicted to occur mainly when a car has stopped due to an accident or when all of the power supply in the vehicle has been disabled. Therefore, the cooling system needs to depend only on natural air cooling to transfer heat from inside the system to outside; therefore, we will need to utilize a natural air cooling system. The paraffin PCM could partially achieve the appropriate temperature range needed for the LiB, but the thermal conductivity of this PCM is quite low (0.2 W m$^{-1}$ K$^{-1}$); as such, it would be quite difficult to release the latent heat. Moreover, the time that this process would take depends on the amount of PCM in the system; as such, heat pipes were used to discharge the thermal energy effectively so to extend the working life of the LiB.

Previous studies have proposed using a PCM with embedded heat pipes so as to increase the effective thermal conductivity of the PCM when charging or discharging thermal energy from a heat transfer fluid in a latent thermal energy system in a concentrating solar power plant (Lee et al., 2005; Tardy and Sami, 2009; Nithyanandam and Pitchumani, 2011; Shabgard et al., 2012; Nithyanandam and Pitchumani, 2014). These studies made important suggestions regarding thermal management methods using a combination of PCM and heat pipes, but there are very large differences from our study in terms of the scale of the device and the melting temperature range.

As for the shape of the LiB, currently there are three types commonly used; cylindrical, rectangular, and laminating. Laminating and cylindrical types are already being used in electric vehicles. In this study, the prototype system adopted an A4-sized laminated-type LiB. Figure 1 shows a conceptual diagram of the LiB cooling system used in this study.

3. Method

3.1 Experimental method

In this study, the cooling system used a paraffin PCM with embedded heat pipes. We intend to measure both the
normal heat emission of the LiB in the charging and discharging states, and the abnormal heat emission of the LiB during thermal runaway. Systems only using heat pipes have already been reported upon (Nelson et al., 2002; Zolot et al., 2002; Mahamud and Park, 2011), and they revealed that heat pipes are suitable for such a system. Each battery in our device was in contact with a number of narrow heat pipes, and the surrounding space of the LiB was filled by the PCM. The cooling system had two heat transfer routes through the heat pipes from the surface of the LiB to the outside of the device, namely (1) LiB–HP–outside and (2) LiB–PCM–HP–outside, as shown in Fig. 1. It seemed as if there was a relatively large amount of thermal resistance between the LiB surfaces and the heat pipes that came into contact with them, but the thermal resistance must have been quite small between the LiB surfaces and the PCM, and between the PCM and the HP surfaces because the PCM was poured in the liquid phase into the space around the LiB and HPs before solidifying, which produced an almost ideal contact interface between the materials. Cooling fins on the condensation area of the heat pipes released the thermal energy into the atmosphere.

Four A4 sized mimic battery were made, as shown in Fig. 2, in which a polyimide heater (194 × 144 × 0.2 mm$^3$) was placed between two aluminum plates (200 × 175 × 4 mm$^3$) and was covered with a laminated film composed of synthetic resin and aluminum foil. A vinyl chloride (CH$_2$=CHCl) container (inner height = 220 mm, inner width = 200 mm, inner depth = 49 mm) contained four mimic batteries, as shown in Fig. 3. The thickness of the container body was 10–35 mm, and its thermal conductivity was 0.17 W m$^{-1}$ K$^{-1}$. A cooling unit composed of 20 heat pipes and 10 cooling fins was put in the condensation area, as shown in Fig. 4. The HPs had an inner radius of 9 mm, length of 220 mm, width of 10 mm, and a thickness of 3 mm, which resulted in the flat shape at the evaporator area. The working fluid was pure water.
This test module considered a potential size miniaturization that may be needed for future EV applications, and the length of the condensation part of the unit was 80 mm, while the ratio between the evaporation and condensation areas was 4:3. In this prototype setup, little consideration was given to the capillary limit and the subsequent maximum amount of heat that could be transported during the design of the length of the heat pipes. The cooling fins were designed so that there would be 7.5 mm of space between each element. Overall, the maximum heat release of this system was at 70 °C – 80 °C, which was when abnormal heat emissions would occur. A natural convection heat transfer was assumed for the cooling fins, and the amount of heat release, $Q_{\text{fin}}$, is given by Eq. (1):

$$Q_{\text{fin}} = 2A_{\text{fin}} h_{\text{fin}} \Delta T_{\text{fin}}$$

(1)

$$h_{\text{fin}} = \sqrt{\left\{ 576 \left( Ra_L \cdot \left( \frac{S}{L} \right)^4 \right)^{-2} + 2.87 \left( Ra_L \cdot \left( \frac{S}{L} \right)^{1.2} \right)^{1/2} \right\} \cdot \frac{k}{S}}$$

(2)

$h_{\text{fin}}$ is expressed in Eq. (2) by the natural convection heat transfer caused by two vertical parallel plates (Bar-Cohen and Rohsenow, 1984). The theoretical values of $h_{\text{fin}}$ and $Q_{\text{fin}}$, which were calculated using Eqs. (1) and (2) at 25 °C, were plotted in Figs. 5(a) and (b), respectively. The position of the fin temperature was represented at the fin center. It is reasonable assumption because the heat pipes were connected at many positions to spread in the whole plane of the fins as shown in Fig. 4.

RT50 (Rubitherm GmbH, 2016) was applied to the PCM in the test module; the physical properties of RT50 are shown in Table 1. RT50 is a paraffin wax PCM with a fusion temperature range of 46 °C – 50 °C. Previous studies have recommended the fusion range of the PCM used in an LiB be mostly 40 °C – 44 °C because the optimum temperature range for operating LiBs is approximately 15 °C – 20 °C (Al-Hallaj and Selman, 2000; Khaete et al., 2005; Mills and Al-Hallaj, 2005; Kizilel et al., 2008; Rao and Wang, 2011). However, the aim of the present study is to explore countermeasures for the abnormal heat emission of LiBs that eventually leads to thermal runaway; as such, we decided to use an organic PCM with a somewhat higher melting temperature. In the test module, 842 cm$^3$ of RT50 was filled as the PCM, and the total amount of latent heat was $1.24 \times 10^7$ J.
Fig. 4  Heat sink unit constructed with heat pipes and cooling fins. (a) The design drawings, (b) The shape of the heat sink, as viewed from the front.

Four kinds of setup were made for the experiments. All of the experiments were conducted with 25 °C being the initial temperature:

(1): Only four mimic batteries were put into the test module, and the PCM and cooling units that contained the heat pipes were removed. This was the “No device” setup.

(2): Four mimic batteries and the PCM were put in the test module, and the cooling units that contained the heat pipes were removed. This was the “PCM” setup.

(3): Four mimic batteries and cooling units that contained heat pipes were put into the test module, and the PCM was removed. This was the “HP” setup.

(4): Four mimic batteries were put into the test module along with the PCM and cooling units containing the heat pipes. This was the “HP + PCM” setup.

In all of the experiments using the mounted four pieces mimic batteries, only the mimic battery located in the center (i.e., the one that was second from the most outside battery) was imposed electric current and thus heated by 400 W. The heater power was estimated from results of short circuit experiments using an LiB (laminated-type) that had lithium iron phosphate (LiFePO₄) as its anode (rated capacity = 22 Ah). The only parameter of the experiment is the surface temperature in the plane central part of the mimic battery on which the electric current was imposed. The surface temperature was measured by a K-type sheathed thermocouple installed on it. The data logger (GRAPHTECH, GL820) recorded the measurement results every one second.

3.2 Numerical analysis

In this study, numerical simulations were performed using the general purpose software for computer fluid
dynamics, ANSYS Fluent (ver.14.5) (ANSYS Corp., 2016); these simulations were used to study the details of the experimental results and to examine the characteristics of the prototype cooling system. The phase change of the PCM was calculated by applying an enthalpy method about the phase change. The calculation model is shown in Fig. 6; the model corresponds to the “HP + PCM” setup. The boundary surfaces that came into contact with the atmosphere were assumed to have a proper heat transfer coefficient to the outside ambient temperature. Our analysis of the heat transport in the PCM only looked at heat conduction and neglected the convection effect. It is because the phase change calculation considering convection was not easy technically. The thickness of each cooling fin was considered to be 1.0 mm in the calculation model, despite being 0.3 mm in the real test module; this was because the minimum size of the hexahedral cells in the calculation model was 0.6–1.2 mm. The discretization of the calculation cells in the simulation model is shown in Fig. 7. Power of 400 W was imposed only to a battery located in the center, which was the same as in the experimental condition.

![Figure 6](image6.png)

**Fig. 6** The calculation model corresponding to the experimental device. (a) View from the front, with the main dimensions provided. (b) View from the top, with the main dimensions provided. (c) Detail of the cooling fins, with the dimensions provided. (d) General overview of the device. (e) Cross-sectional view of the device, as if it were viewed from the front of the device.

![Figure 7](image7.png)

**Fig. 7** Meshes in the calculation model. (a) Overview of the meshes. (b) Details of the calculation meshes in the heat pipes and cooling fins. (c) Details of the calculation meshes at the center, as viewed from the front, including the heat pipes, case, and PCM. (d) Overview of the cooling unit with the produced lattices.
The physical properties used in the calculation model are shown in Tables 1–5. In the calculation model, the physical properties of the PCM, cooling fins, apparatus container, and atmospheric air were the values of RT50, aluminum, vinyl chloride, and air at 25 °C, respectively. The effective thermal conductivity of the heat pipes was set to be 30 times that of copper, which is 11940 W m⁻¹ K⁻¹ (Legierski et al., 2006; Panigrahi, 2016). The density and specific heat were assumed by considering the volume fraction of each element in a heat pipe as being in an airtight container and being a working fluid, respectively. The properties of the simulated cells (i.e., mimic batteries) were difficult to decide upon, but some assumed values were used. In the model, the heat transfer coefficient of the boundary surfaces that came into contact with the atmosphere was set to be 5 W m⁻² K⁻¹ at the condensation area of the heat pipes and cooling fins and 3 W m⁻² K⁻¹ at the outside of the main body and the upper surface of the PCM. We estimated that there was contact thermal resistance at the interface between the battery’s surface and the heat pipe. In the calculation, the contact thermal resistance assumed a 0.1-mm virtual thickness of the boundary surface with a thermal conductivity of 0.84 W m⁻¹ K⁻¹. Of the four mimic batteries, only the one in the center was heated by 400 W, which was the same as in the experimental conditions. The calorific value per unit volume of the heater was set to be $1.31 \times 10^6$ W m⁻³. Unsteady calculations were performed for 1,800 s by the numerical model, with 0.1 s time step used.

### 4. Results and Discussions

Figure 8 (a) shows the results of the temperature measurements in the heated mimic battery in the test system of the four experimental setups. Figure 8 (b) shows and compares the temperatures in the heated mimic battery until 1,800 s between the experiments and the numerical model. Figure 9 shows the y-z plane of the contour views displayed in Fig. 10 and 11. Figures 10 and 11 describe the simulated results of the temperature distribution and the liquid phase ratio in the center of the cross-sections of the setups at 300, 600, 900, and 1,800 s. To investigate the heat flow inside the system, the simulated results of the amount of heat transferred from the heated mimic battery to the adjacent heat pipes, from the heated mimic battery to the PCM, from the heat pipes to the cooling fins, and the ratio of the liquid phase in the PCM are all shown in Fig. 12. Table 6 shows the surface temperature at each elapsed time in four setups and Table 7 shows the ratio of the total calorific value (400 W) of the quantity of each heat flow at 1,800 s, as an example.

### 4.1 Experiments

From Fig. 8 (a) and Table.6, After 120 s from the start time of the experiment, the temperature of “No device” setup exceeded 80 °C, becoming dangerous temperature leading to thermal runaway. After 240 s from the start time, the temperature of “PCM” and “HP” setups were exceeded 80 °C. Afterwards, the experiment of “No device” setup was finished because the temperature gradient became suddenly large after 300 s. After 720 s, all experimental setup was...
exceeded 80 °C. The experiment of “PCM” was finished because the temperature gradient became suddenly large after 1500 s. The temperature difference between “HP” and “HP + PCM” setups became 39.3°C, 32.5°C and 28.4 °C at 1500 s, 2700 s and 3600 s, respectively. The time to reach 80°C, which is dangerous temperature leading to thermal runaway, are 104 s, 187s, 216 s and 708 s in “No device”, “PCM”, “HP” and “HP + PCM” setups, respectively. The condition of “HP + PCM” setup extended the time to reach 80°C, by about 7-times more than “No device” setup.

Initially, from the result of the “No device” setup, as has been predicted, as the test module did not have any cooling measures, it could not control the temperature increase under the assumed abnormal heating condition.

As for the “PCM” setup, basically, it could not control the temperature increase under the assumed abnormal heating condition. However, from 600–900 s, it stopped increasing and stayed within a range of ±3 °C. This result shows that the temperature rise in the mimic battery was restricted by the latent heat capacity of the PCM. The reason why the temperature remained at a temperature somewhat higher than that of the melting point of the PCM is thought because although the temperature around the melting interface of the PCM was near the material’s melting point, there was a large temperature gradient inside the melted PCM because of its small thermal conductivity (0.2 W m⁻¹ K⁻¹). To balance the heat from the mimic battery and the melting rate of the PCM, the temperature of the melted PCM, and the mimic battery adjacent to it, increased to approximately 120 °C. Figure 8 (a) also shows that after most of the PCM had melted, the temperature rose again. This result led us to believe that the melting point of the PCM, and its quantity in the setup, greatly influences the temperature that is maintained and the total amount of heat absorbed.

In the “HP” setup, it could not control the temperature increase under the assumed abnormal heating condition either. However, the temperature became almost steady at this point, as it changed only within ±10 °C between 1,800–3,600 s (at which point the experiment ended). At the end of the measuring time, the inner temperature was 147.2 °C. Under this condition, heat generated inside the system was transported to the ambient air through the heat pipes and heat sink; when both of the amounts of heat were equal to one another, the temperature became stationary. The heat transfer rate of the fins can be determined by Eq. (2), and the heat removal from the fins was determined by the temperature difference, AT, between the fins and the ambient air. As the fins were tightly connected with the heat pipes and because the temperature difference between the two ends of the heat pipe itself was small, the fin temperature was strongly related to the temperature inside the system. In this experiment, depending on the thermal efficiency of the particular fins used and the resultant fin-surface temperature, the temperature of the mimic battery became approximately 140 °C to balance out the inner heat generated and the heat lost to the air. Therefore, if the efficiency of the fins is improved, the temperature at which the mimic battery is maintained could be lowered.

In the “HP + PCM” setup, the inner temperature of the mimic battery exceeded 80 °C after 708 s, and it reached 100.8 °C after 1,800 s. The inner temperature at the end of the measuring time (i.e., 3,600 s) was 118.8 °C. The experiment indicated that by using this experimental setup, the inner temperature of the mimic battery was 28.4 °C lower at the end of the measuring time than in the “HP” setup. However, under this condition, the temperature still kept increasing after 3,600 s, and it seemed to take longer to reach a steady state. The final steady temperature will be determined by the thermal performance of the heat sink. The PCM is thought to have reduced the increase in the heating rate of the mimic battery in this setup. The reason why a very long time was needed to reach the steady state is because the thermal conductivity of the PCM used is extremely small (0.2 W m⁻¹ K⁻¹). We think that if the thermal conductivity of the PCM was increased, the system would have a more evenly distributed temperature inside the PCM, which would reduce the rate at which the temperature increases.

| Time [s] | “No Device” | “PCM” | “HP” | “HP+PCM” |
|----------|-------------|-------|------|----------|
| 0        | 25.7        | 26.5  | 26.2 | 25.8     |
| 60       | 58.9        | 50.5  | 51.4 | 44.3     |
| 120      | 88.2        | 65.4  | 66.2 | 53.4     |
| 240      | 131.4       | 91.2  | 82.9 | 60.7     |
| 300      | 143.9       | 100.6 | 88.8 | 63.9     |
| 480      | -           | 115.6 | 102.9| 72.5     |
| 720      | -           | 123.7 | 116.1| 80.3     |
| 900      | -           | 124.8 | 123.2| 85.5     |
| 1500     | -           | 141.5 | 135.4| 96.1     |
| 2700     | -           | -     | 143.7| 111.2    |
| 3600     | -           | -     | 147.2| 118.8    |
4.2 Numerical Calculation

Figure 8 (b) shows a comparison between the temperature of the mimic battery in the experimental setup of “HP + PCM” and in the simulation; we see that there is quite good agreement between the two until 900 s, when the temperature of the calculation result started to be a little higher. It is thought that this difference was mainly due to the convection heat transfer that took place in the melted PCM in the experiment. As shown in Fig. 11, the calculation model indicated that the majority of the PCM had melted after 900 s, which was also observed in the experiment, because the color of the PCM changed from white to transparent when it melted. As the viscosity of the melted PCM (RT50) is small, the onset of melt convection can be predicted in the experiment, although a flow measurement was not done here. On the contrary, the flow of the melted PCM was ignored in the calculation, although the phase change from solid to liquid and the heat of fusion were incorporated in the calculation. In the experiment, convection in the melted PCM increased the heat transferred from the mimic battery to the PCM.

As can be seen in Fig. 12, the calculation result shows that the heat directly transferred from the mimic battery to the heat pipes was larger than that from the mimic battery to the PCM. Table 7 outlines values obtained from the calculation model, and approximately 70% of the total calorific value (i.e., heater input) was transferred from the heat pipes to the cooling fins, while approximately 30% was absorbed by the PCM after 1,800 s; this is due to the quite small thermal conductivity of the PCM (0.2 W m$^{-1}$ K$^{-1}$), which meant that less was transferred from the mimic battery to the PCM. Moreover, Fig. 12 indicates that, until 900 s, the amount of heat transferred from the heat pipes to the cooling fins was quite different from that from the mimic battery directly to the heat pipes. This means that the heat from the battery to the heat pipes was not fully radiated to the cooling fins and to the ambient air during this period, and the remaining heat was used to increase the temperature of the heat pipes themselves. Thus, the hotter heat pipes are thought to have radiated heat to the PCM, which was subsequently consumed during the melting of the PCM (i.e., latent heat) and the temperature increase in the melted PCM (i.e., sensible heat). Therefore, we believe that the temperature difference (approximately 30 °C–40 °C) between the mimic batteries in the “PCM” setup and the “HP + PCM” setup was not only due to the melting and temperature increase of the PCM but also due to a combination of these two factors and the heating of the heat pipes. The amount of heat radiated from the fins was determined by the temperature difference between the fins and the ambient air and the efficiency of the fin system, which can be calculated using Eqs. (1) and (2). Thus, to improve the cooling ability and lower the battery temperature, the efficiency of the fin system needs to be increased so that there is less of a temperature difference between the fins and the ambient air. From Fig. 12, we can also see that a little too much time was needed for the fins to become fully hot and the heat release to have increased enough. This depends on the heat capacity of the fins and the heat pipes. The total volume of the fins and the long heat pipes used should be decreased to shorten this time. Aside from the fin system, the contact thermal resistance between the mimic battery and the heat pipes did not seem to be small, but this should nevertheless be decreased to improve the heat transport. Moreover, the effective thermal conductivity of the PCM could be raised by incorporating techniques and ideas from the field of materials science and engineering. Such improvements should lead to more rapid heat transfer in the cooling system.
Table 7 The amount of heat transferred at 1,800 s.

|               | Total | Heat transfer from HP to Cooling fins | Absorbed heat in PCM | Heat release from Others |
|---------------|-------|---------------------------------------|----------------------|--------------------------|
| Calorific value (W) | 400   | 275                                   | 123                  | 2.0                      |
| Ratio (%)      | 100   | 68.8                                  | 30.7                 | 0.5                      |

Fig. 9 The y-z plane of the contour views displayed in Fig. 10 and 11

Fig. 10 Contour views of the time variation of the temperature distribution in the calculation model at the cross-section of the y–z plane indicated in Fig. 9 (at x = 250.5 mm) at (a) 300 s, (b) 600 s, (c) 900 s, and (d) 1,800 s.

Fig. 11 Contour views of the time variation of the mass fraction of the liquid phase in the calculation model at the cross-section of the y–z plane indicated in Fig. 9 (at x = 250.5 mm) at (a) 300 s, (b) 600 s, (c) 900 s, and (d) 1,800 s.
5. Conclusion

In this study, we looked to improve the safety performance of a cooling system used for Li-ion batteries, which are used in electric vehicles. These batteries suffer from thermal runaway in the case of abnormal heat emission, and so we developed a prototype cooling system combining PCMs and heat pipes. Our test module used mimic batteries to simulate real A4-sized laminated-type LiBs. Experiments were conducted at abnormal heating conditions, and numerical simulations were performed using ANSYS Fluent software. We have made the following conclusions based on our findings:

(1) Under the condition where abnormal heating was imposed to simulate thermal runaway using a cooling system with a PCM and heat pipes, the temperature of the mimic battery did not exceed 100.8 °C until 1,800 s after the start. We can, therefore, confirm that the cooling ability of this system was somewhat successful. This result was mostly reproduced by the simulation model.

(2) In the prototype system, when both the PCM and heat pipes were used, the temperature of the mimic battery was approximately 30 °C lower than when only heat pipes were used from 480 s to 3600 s, after the start time of the experiment. This was due to the latent heat of fusion of the PCM, the sensible heat of the melted PCM, and a combination of these and the heated heat pipes.

(3) The key elements determining the temperature that the battery reached after a long period of time were thought to be the heat pipes and the fins. Considering that the temperature at the end of the heat pipes was near that of the temperature of the battery inside the container and that the temperature difference between the fins and the ambient air was small, we believe that a better design of the fins would lead to improved heat transfer.

(4) The melting temperature of the PCM and the amount used in the system could be further adjusted by considering the necessary amount of total heat absorption of the PCM and the desired temperature of the cooling system.

In the present experiment, the temperature of the mimic battery finally became larger than 80 °C, which was the temperature we wished to achieve to restrict the thermal runaway of the LiB. Although the present cooling system was not wholly satisfactory, we believe that this system (i.e., with the paraffin PCM and heat pipes) will be very promising for thermal management systems, if the efficiency of the fin heat sink and the melting temperature and the amount of PCM used are appropriately adjusted.
This study used mimic batteries from an electric heater as a substitute for a LiB. In the future, we plan to perform short circuit tests using real LiB cells to obtain more practical data.

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