EXPERIMENTAL AND MODELING STUDY ON A FUTURE COOLING SYSTEM FOR LITHIUM-ION BATTERY OF ELECTRIC VEHICLE

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ABSTRACT

Electric vehicles (EV) are already commercialized and their market has been expanding gradually. Lithium-ion battery (LIB) is widely used for their power source of many EVs. It is known that LIB generates heat during its usage and that the proper temperature control is necessary for extending its life and securing its safety. Our laboratory proposed a novel cooling technology utilizing phase change material (PCM) and heat pipes for laminating-type LIB cells. We built prototype setups and investigated their heat transfer characteristics. As phase change material, paraffin-based material was adopted. Stick-shaped flat heat pipes were used in the experiments. A setup of one-fourth of the real size apparatus and a real size apparatus were actually built and the temperature transition was measured after the LIB cell started emitting heat. From the experiments, we found that the cooling ability of those systems were satisfactory in terms of LIB life and safety. At the same time, we did modeling studies using a simplified mathematical model (lumped model) and a precise three dimensional numerical model (ANSYS FLUENT model). With the modeling studies, we were able to find some future methods for obtaining more cooling ability and more compactness of the system. The increase of the thermal conductivity of the phase change material was very effective for the cooling ability, and the arrangement of heat pipes and heat sinks will be a key issue for future technology of LIB cooling system.

1. INTRODUCTION

In recent years, it is expected that electric vehicles require high-performance battery to use energy efficiently because electric vehicles can be driven by the battery power converted from new energy such as wind or solar power. Thus, high-performance battery can contribute to use the energy efficiently. Therefore, high capacity and high output performance of Lithium-ion Battery (LIB) has been advanced rapidly. However, it leads to risks of deterioration of the performance and thermal runaway for the temperature increases in the battery cells due to the high heat generation in charging and discharging of the battery. Ramadass et al reported LIB decreases the life and the capacity when it reaches higher than 45 degrees Centigrade[1]. From these points, optimization of the battery characteristics and improvement of the temperature management are necessary to achieve high safety of the LIB.

In this study, we proposed a novel cooling system using heat pipes with Phase Change Material (PCM) [2][3]to solve the above mentioned problems. In normal cases at low heat emission such as during normal driving, the temperature of the battery should be kept under 45 Centigrade. In abnormal case such as thermal runaway, the system should provide enough time until the passengers can be evacuated from the vehicle. In this paper, the author introduces the recent studies in the author’s laboratory and major outcomes. The author also refers to necessary developments in the future of the research.

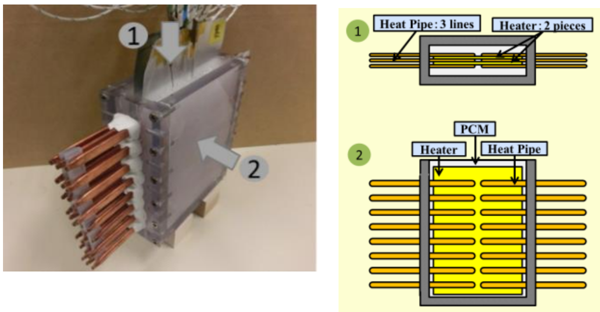
This report consists of small 1/4 scale setup study and real size setup study. The latter utilized real LIB cells to investigate practical merit of the system.

2. STUDY ON 1/4 SCALE SETUP

2.1 Experiment

Among several types of the LIB, laminated type is expected to be widely used in future because its cooling performance is quite well. However, internal short-circuit in the battery and so on cause abnormal heat in the battery cell. This study focused on laminated type LIB. Input power were normal heat (1C, 2C, 3C or 5C) and abnormal heat. 1C is a current value when the battery was discharged the electric capacity in one hour, 2C is 30 minutes, 3C is 20 minutes and 5C is 12 minutes.

In the experiments of 1/4 scale of the real battery size, we used electric heaters as a substitute of the real cell. The



(a)Photo of 1/4 scale setup (b)Inner structure
Fig.1 1/4 scale experimental setup

input power was assumed to be 0.75W at charge and discharge of 1C, 2.5 W at 2C, 5 W at 3C, 12.5 W at 5C, 100 W at the abnormal heat generation, respectively. As in Fig,1(b), 2 pieces of substitute electric heater and many stick-type heat pipes with effective diameter of 6 mm were built in the container with RT-50 (paraffin, melting point: 49 degrees, developed by Rubitherm Technologies GmbH) , which was adopted as PCM material in this study. The temperature was measured at the center and inside the electric heater plate.

2.2 Lumped model

Ojiro et al. modeled the above 1/4 size system by using a one-dimensional lumped modeling technique[4]. The outline of the modeling is shown in Fig.2. The heat inflow or outflow was calculated between the lumps. The temperature of a lump was deduced by heat balance. The melting of PCM was simulated by using the temperature recovery method[5]. The thermal conductivity of the heatpipe was assumed to be 100 times larger than that of copper. The heat transfer coefficient of their condenser was assumed to be in the order of air cooling.

2.3 Results and effect of PCM's thermal conductivity

The measured temperature transitions are shown in Fig.3. When the applied currents were 1C, 2C and 3C, the temperature was well kept under 45 Centigrade. In 5C, the temperature went over 45 Centigrade slightly, but kept under 50 Centigrade. Since 5C usage takes place during steep slope driving, it can be stated that the temperature was well controlled in 1C to 5C heat emission.

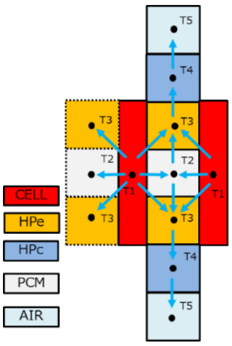


Fig.2 The outline of lumped model

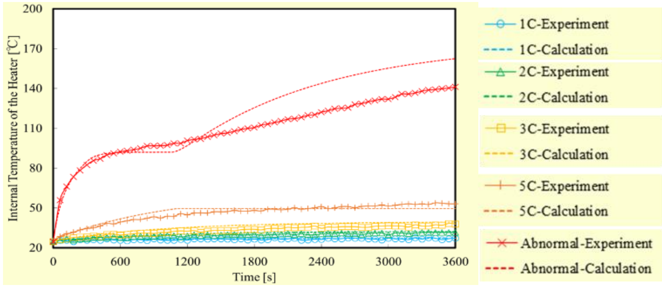
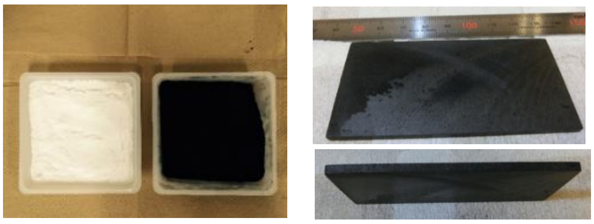


Fig.3 Measured temperature in 1/4 setup experiments

In abnormal heat emission, the temperature went over 80 Centigrade, which is thought to be dangerous to LIB. With the excessive heating, the system now has to secure time for passengers to evacuate from the car. From this experiment, about 250 seconds could be given to the passenger, which is reasonably good for their safety. The temperature calculated by the lumped model remarkably well reproduced in 1C to 5C cases. In abnormal case, the deviation from the experiment gradually increased after 1200 seconds. As is well known, paraffin has very small thermal conductivity in general. Thus, for our purpose, the increase of effective thermal conductivity will improve heat transfer. The partner research group in Hokkaido University developed a PCM composite of paraffin and carbon fiber powder, which is shown in Fig. 4. Before the usage of the composite plates in our experimental setup, we predicted its effect in the abnormal heat emission case, by using the lumped model, which was assured in the comparison in Fig.3. The calculated results are shown in Fig.5.


(a) (b)(top) (c) (bottom)
Fig. 4 (a)powder of paraffin(left) and carbon fibers(right), (b)composite plate, (c)side view of the plate.

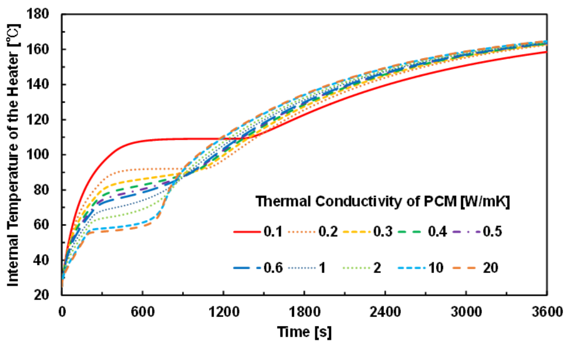


Fig.5 Predicted results with increased thermal conductivity of PCM (in abnormal heat emission)

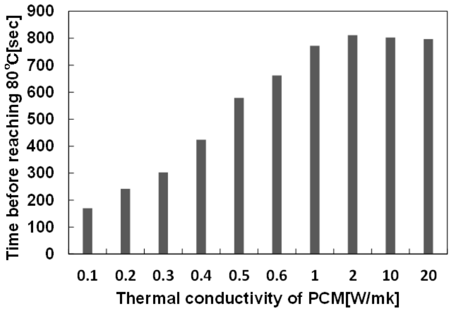


Fig. 6 Predicted time before reaching 80 Centigrade

Also we investigated the time before the heater (substitute of cell) reaches 80 Centigrade from the calculated results. The result is shown in Fig.6. From Figs. 5 and 6, it is clear that the increase of the thermal conductivity of the PCM could well decrease the heater temperature and could extend time before reaching 80 Centigrade. Thermal conductivity of pure paraffin was about 0.2 (W/mK). As Figs. 5 and 6 show, the merit of the increased thermal conductivity seemed saturated when its value became 2 to 10 (W/mK).

2.4 Precise numerical models

The author's group has ANSYS FLUENT software, which is well-known commercial software for thermofluid problems. The author's group constructed a detailed three dimensional models to represent the experiments in the preceding sections. The outline of the model is shown in Fig. 7. For practical necessity, fin-type heat sink system was added in the modeling. Sample of the simulated results is shown in Fig.8. The details of the results are not shown here. Similar modeling will be used in the study of 1/1 scale setup.

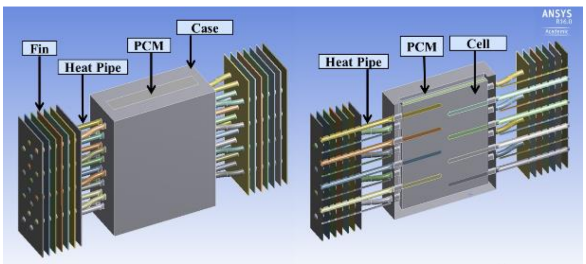
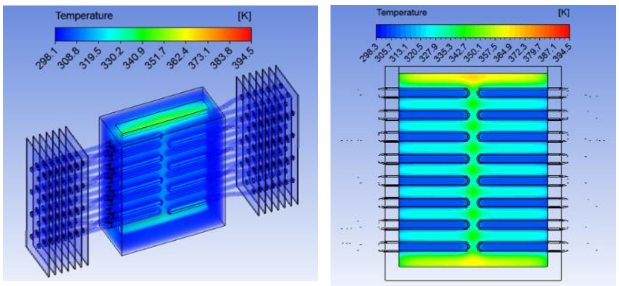
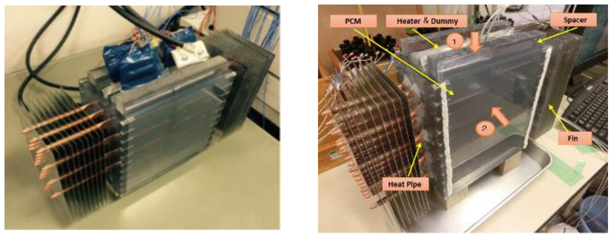


Fig.8 FLUENT modeling with fin-type heat sinks



(a)Temperature outline (b)Inside temperature

Fig.9 Sample results of FLUENT models (1/4 size)



(a)1/1 setup with real LIB (b)1/1 setup with heater

Fig.9 1/1 scale experimental setups

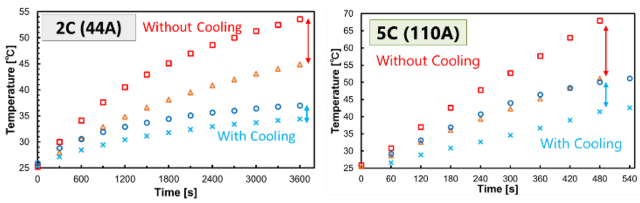
3. STUDY ON 1/1 SCALE SETUP

3.1 Experiment

We prepared 1/1 scale setup with real LIB cells. Fig. 9(a) shows the setup with real LIB cells. The LIB cells were connected to charging and discharging electronic equipment. On the other hand, to represent abnormal heat emission case, we also prepared 1/1 scale setup with substitute electric heater as shown in Fig.9(b). 400 watts was imposed to the heater. It is because the onset of short circuit with real LIB is very dangerous in our laboratory. In those setups, fin-type heat sinks were attached to simulate practical situation.

3.2 Results

The cell temperature measured with the real LIB cells (Fig.9(a)) is shown in Fig.10(a)(b). In these experiments, paraffin PCM (RT-50) and heat pipes were incorporated in the setup(with cooling). As comparison, data without PCM nor heatpipes, are also shown(without cooling). The difference between □ and △ symbols and between ○ and × symbols, means the temperature distribution at the cell surface in Fig. 10. The temperature at the inner center of the cell was □ and ○, and that at the side periphery was △ and ×. It was apparent that with this cooling system of PCM and heatpipes can offer much lower temperature of the cell. In 2C case, the temperature was lower than 45 Centigrade, and in 5C, the temperature reached about 50 Centigrade, but much lower than the case without cooling. As shown in Fig.11, even in abnormal heat emission case, this system with PCM and heatpipes could offer most extended time before reaching 80 Centigrade. Therefore, we think from these results that the concept of the system with PCM and heatpipes was well assured and the practical merit was successfully indicated. The experiment with the developed PCM composite with increased thermal conductivity (Fig.4(b)) is now going on. The result will be shown in the conference.



(a)Temperature in 2C (b)Temperature in 5C

Fig.10 Measured data with real LIB cells (1/1 scale setup)

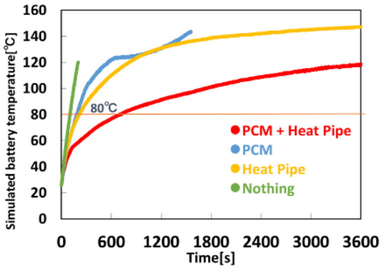


Fig.11 Measured temperature with substitute heater in abnormal heat emission (1/1 scale setup)

4. SUMMARY

This study proposed a hybrid cooling system for the thermal management of a secondary LIB utilizing a combination of heat pipes and PCM. 1/4 scale size setup and 1/1 scale setup were constructed and studied. In 1/1 scale setup, real LIB cells were used. In conclusion, in 1C, 2C and 3C charging and discharging cases, this system could keep the cell temperature under 45 Centigrade. Also in 5C case, the temperature was controlled under about 50 Centigrade. In abnormal thermal runaway case, this system could extend time before the cell reaches 80 Centigrade, which is thought to be dangerous temperature.

5. FUTURE DEVELOPMENT

The author thinks that the arrangement of PCM and heatpipes would be reconsidered in future. More optimized structure could be found. For example, if the thermal conductivity of PCM is much more raised, heatpipes do not have to penetrate into the PCM. Only the periphery of PCM plates would be cooled by heat pipes, heatsinks, or other cooling devices. In any case, the possibility of developing more compact and efficient system still remains.

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