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Simulation of Battery Cell Heating Behavior Using a Thermal Model

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ABSTRACT: A new thermal emulator that can simulate the heating behavior of real battery cells has been developed as a useful solution for the thermal management design of battery packs. The thermal emulator consists of a controller, a power supply, and a heater cell with the same shape as the real cell. The controller has a table of operating conditions obtained from the real cell and converts the operating conditions of the cell, such as current and initial SOC (State of Charge), into the operating current of the heater cell. The heater cell consists of a heater and thermal diffuser. Its structural design is based on a thermal network model that reproduces the thermal behavior of the real cell. The prototype thermal emulator simulates the surface temperature distribution of the real cell with an accuracy of ±2°C. By integrating this thermal emulator in a battery pack instead of real cells, thermal design and physical verification of the battery pack can be performed even if real cells are not available in the early stages of battery pack development.

KEY WORDS: thermal emulator, thermal network model, thermal management, EV, battery pack

1. INTRODUCTION

The proliferation of electric vehicles (EVs) is accelerating toward a carbon-neutral society [(1)]. However, for EVs to be used in earnest as replacements for internal combustion engine (ICE)-based vehicles, many challenges remain, including high cost, insufficient cruising range, long charging times, and a lack of charging stations. Therefore, further improvement and cost reduction of battery energy capacity and output performance is needed. At the same time, vehicle thermal management is becoming increasingly important to maximize the effective use of battery energy. In recent years, advanced heat management technologies have been developed to interconnect coolant and refrigerant pipes to cool and heat each part of the vehicle, which were previously controlled independently, and to distribute heat throughout the entire vehicle [(2-4)].

The battery pack is one of the major heat sources in an EV and requires careful thermal design. Large current flow during rapid acceleration and deceleration of the vehicle and during charging generates significant heat due to the internal resistance of the battery. Since battery operation at high temperatures accelerates degradation and increases the risk of fire, heat dissipation to outside of the pack must be designed appropriately.

Figure 1 shows a schematic of the V-process in EV and battery pack development. Based on EV system definition, battery pack performance requirements (capacity, output, dimensions, weight, durability, reliability, and safety) are determined. Although pack design is generally conducted through model-based development (MBD), it is necessary to verify with real batteries that the heat dissipation performance is as designed. However, it is difficult to efficiently perform prototyping and physical verification of battery packs for several reasons: 1) In early stages of battery pack development, the cells used in the packs are often still under development and not available in sufficient quantities, 2) Cells under development are not fully verified for safety and have relatively high safety risks, and 3) A lot of time is required to adjust the state of charge (SOC) of the real cell.

As a means of easily conducting heat generation experiments on battery packs without real cells, authors have attempted to construct a cell thermal emulator by modeling heat generation behavior of real cells using thermal network methods and replacing it with a map of device power supply operating conditions. This paper describes the basic configuration of the emulator and simulation results using a prototype emulator.

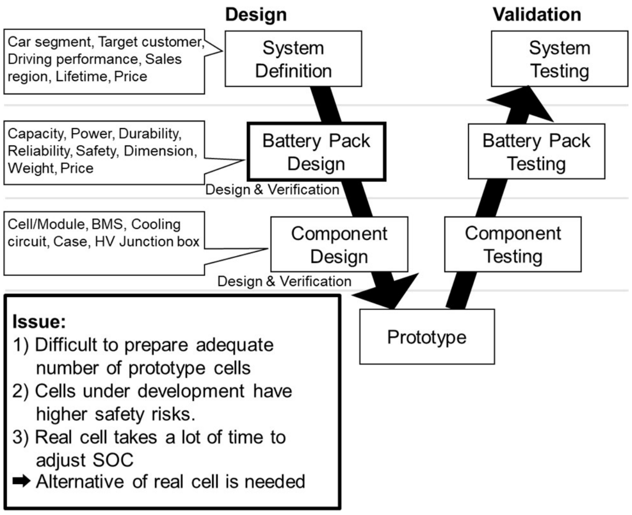


Fig. 1 Electric vehicle development process

2. Concept and Design

2.1 Basic configuration

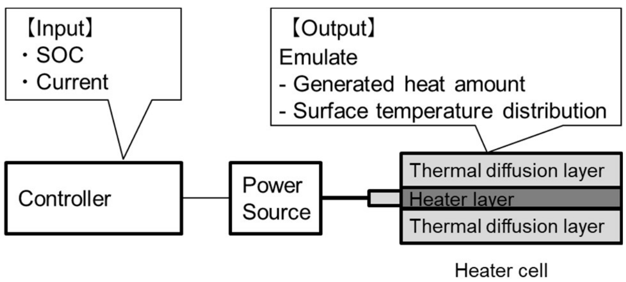


Fig. 2 Schematic diagram of cell thermal emulator

Figure 2 shows a schematic of a cell thermal emulator. This thermal emulator consists of a heater cell, a power supply, and a controller.

The heater cell has a layered structure with a thermal diffusion layer on both sides of the heater layer (i.e. the heating layer). In the plane, the heating section is divided into several segments, with each segment having a different resistance and heat capacity value based on a thermal network model [5] created from measured data of the thermal behavior of the real cell. Thermocouples are installed on the surface of the heater cell to measure the surface temperature.

The controller sequentially instructs the power supply on the driving conditions based on a map of operating conditions corresponding to the various operating conditions (current, voltage, SOC, temperature) of the actual cells, and the heater cells generate heat with power from the power supply.

2.2 Thermal emulation procedure

Figure 3 shows the process to emulate a real cell with the thermal emulator. The process is performed in the following order.

a) Maps of fundamental cell data (i.e., SOC-OCV, DCR-SOC, ΔS-SOC, surface temperature distribution) were obtained by charging/discharging a real cell under various conditions (i.e. SOC, charge/discharge current, ambient temperature). Here, OCV, DCR, and ΔS indicate Open Circuit Voltage, DC resistance, and entropy change, respectively.

b) Based on the measurement results in a), a thermal network model of the cell was created. The thermal network model is a circuit model that replaces arbitrary 3D geometry with a circuit consisting of thermal resistance, heat capacity, and heat source. The temperature distribution was simulated by dividing the cell surface into several independent segments. The larger the number of segments, the better the reproducibility of the surface temperature distribution. However, as the number of temperature measurement points increases, the thermal circuit becomes more complex. In this study, a circuit model with 3 x 4 = 12 heat-generating segments connected in parallel was used, which is the same as the temperature measurement points of a real cell. The circuit constants for each segment (i.e., heat capacity and heat transfer/conduction) were determined based on the time constant of the temperature rise of each segment when a step-like current was applied to the real cell.

c) Based on the operation map in a), a map of operating conditions of the power supply to reproduce the same heat generation in the heater cell as in the real cell was created. Here, the current value I_{eml} for the heater cell to show the same heat generation as the actual cell when the real cell is charged (discharged) at a certain current I_{real} was obtained for each condition by the following formula,

$$I_{eml} = \sqrt{\frac{DCR}{R_{heater}} {I_{real}}^2 + \frac{T\Delta S}{FR_{heater}} I_{real}} \qquad (1)$$

I_{eml} : operating current of thermal emulator
R_{heater} : heater resistance of thermal emulator
I_{real} : operating current of real cell
DCR : internal resistance of real cell
ΔS : entropy change of real cell
T : surface temperature of real cell (representative point)
F : Faraday constant.

Here, the heater resistance R_{heater} is designed to be sufficiently larger than the DCR value of the real cell. This design reduces the size of the power supply required to operate the emulator.

d) A heater cell with the same external shape as the actual cell was fabricated. Aluminum was selected as the material for the thermal diffusion layer in the heater cell because it has thermophysical properties like those of the real cell and good machinability; the heat capacity from the heater to the surface was also adjusted for each segment by machining.

e) The heater cell from d) was combined with the power supply and controller to form the thermal emulator system. The emulator is completed by confirming that the heater cell generates heat by specifying the charge/discharge current value and initial SOC and reaches a temperature equivalent to that of the real cell.

f) The completed thermal emulator is housed in a battery pack instead of a real cell and various heat generation experiments on the battery pack (e.g. coolant heat exchange circuit, optimization of heat transfer and insulation materials) are performed.

The real cell and heater cell used in this study are shown in Figures 4 (a) and 4 (b), respectively. A pouch-type cell (Mn-based cathode, 33 Ah nominal capacity) was used as the real cell to be simulated. The heater cell was a laminated structure with a thin-film heater sandwiched between Aluminum plates on both sides, and the space between each 3 x 4 segment was insulated by Plastic plates.

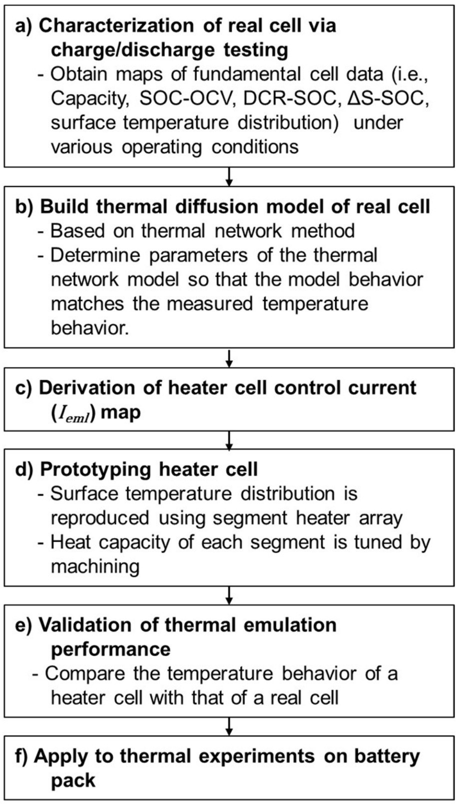
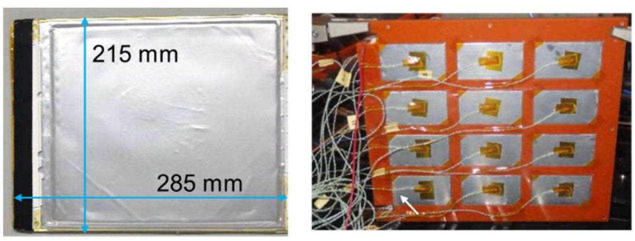


Fig. 3 Process to emulate real cell with the thermal emulator.



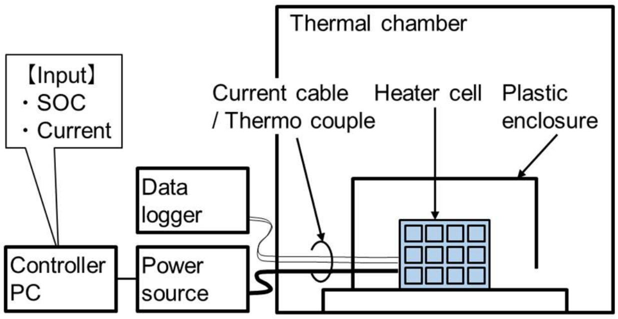
(a) Real cell (Pouch type) **(b) Heater cell**

Fig. 4 Picture of the real cell and the heater cell of thermal emulator

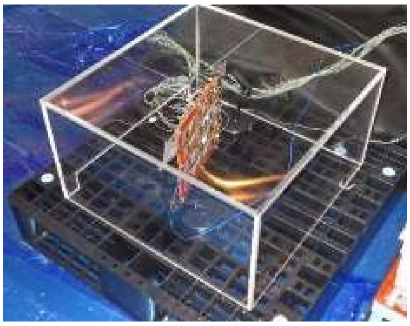
3. Experiment

3.1 Experimental set up

The prototype thermal emulator was evaluated in the experimental system shown in Fig. 5. The heater cell of the thermal emulator was installed in a plastic enclosure inside the thermal chamber to avoid airflow in the thermal chamber and to easily simulate the closed environment inside the battery pack. Current cables from the heater cell and thermocouples were connected to the power supply outside the thermal chamber and to a data logger, which was controlled by a PC.



(a) Experimental setup



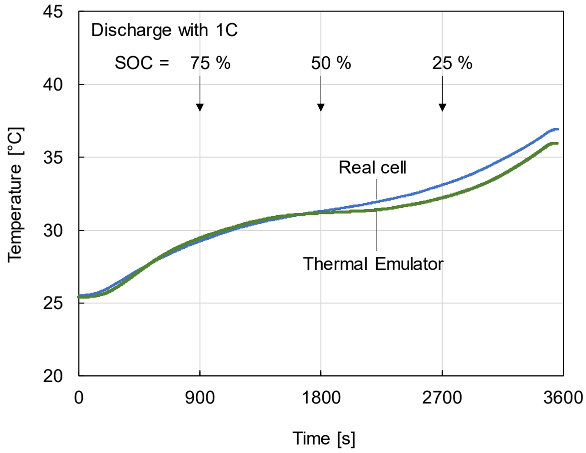
(b) Picture of a heater cell in plastic enclosure

Fig.5 Experimental setup for emulation performance verification

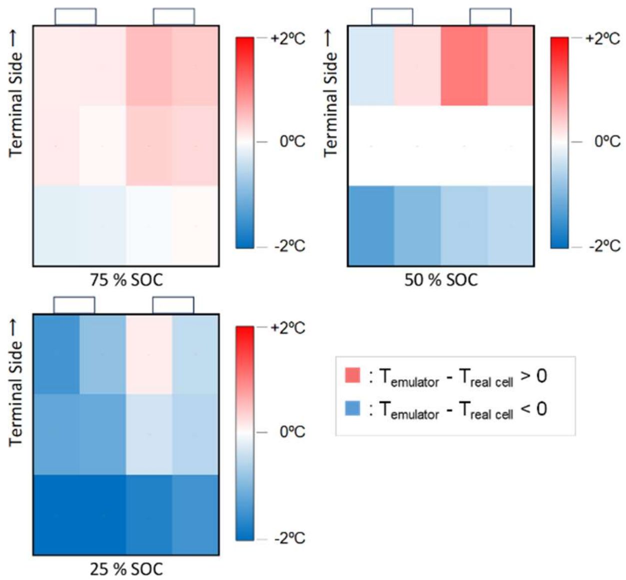
3.2 Experimental result

Figure 6 shows a comparison of surface temperatures in a discharging cell between a real cell and the thermal emulator. Here, the ambient temperature was set to 25°C and the cells were discharged from a fully charged state (100% SOC) at a constant current of 1C (33A) for 1 hour. Fig. 6 (a) shows the average surface temperature over time. The temperature continues to rise during the discharge process. The reason for this is assumed to be that in this experiment, there is no heat dissipation mechanism by thermal conduction such as cell restraint jigs, etc., and heat is readily stored inside the cell. In the region from the start of discharge to 50 % SOC, the temperature transition of the emulator is almost the same as that of the real cell; after 50 % SOC, a slight temperature deviation is observed. The maximum deviation of the average temperature throughout the entire discharge interval was 1.1°C.

Figure 6 (b) compares the surface temperature distributions of the thermal emulator and the real cell at 25 %, 50 % and 75 % SOC, respectively. As shown in Fig. 6 (a), at 75 % and 50 % SOC, there was little temperature deviation between the emulator and the real cell in the center of the cell, and the surface temperature is well simulated. On the other hand, at 25 % SOC, the emulator temperature is at most 2°C lower than that of the real cell, indicating that further adjustment of the thermal circuit model parameters is necessary. However, the emulator can reproduce the heat generation behavior of actual cells with an accuracy of ±2°C, making it useful for verifying the thermal characteristics of battery packs.



(a) Trend of average surface temperature during discharge



(b) Distribution of the temperature difference between the thermal emulator and the real cell

Fig. 6 A comparison of surface temperature between the thermal emulator and the real cell during discharge

4. CONCLUSIONS

A new thermal emulator, a heater device that can simulate the heat generation behavior of a battery cell by modeling based on the thermal network method, was constructed. The following results were obtained from evaluation tests conducted with current, SOC, and ambient temperature as the operating conditions of the heater cell.

▪ From the start of discharge to 50 % SOC, the average surface temperature of the emulator generally matched that of the real cell; from 50 % SOC to 0 % SOC, a slight temperature deviation was observed, and the maximum deviation of the average temperature over the entire discharge interval was 1.1°C.

▪ In the comparison test of surface temperature distribution, the emulator temperature deviation from the actual cell was small, especially in the center of the cell, and the surface temperature was well simulated under the 75 % and 50 % SOC conditions.

Conversely, at 25 % SOC, the emulator temperature was at most 2°C lower than that of the real cell.

As described above, the emulator was able to reproduce the heat generation behavior of the real cell with an accuracy of ±2°C, making it useful for verifying the thermal characteristics of battery packs. Further adjustment of the thermal network model parameters will be necessary to improve the simulation accuracy in the future.

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REFERENCES

(1) Global EV Outlook 2024, IEA, https://www.iea.org/reports/global-ev-outlook-2024/ (accessed Oct. 23, 2024).

(2) F. S. Hwang, T. Confrey, C. Reidy, D. Picovici, D. Callaghan, D. Culliton and C. Nolan, “Review of Battery Thermal Management Systems in Electric Vehicles”, *Renewable and Sustainable Energy Reviews*, Vol. 192, 114171, March 2024.

(3) A. K. Thakur, R. Sathyamurthy, R. Velraj, R. Saidur, A.K. Pandey, Z. Ma, P. Singh, S. K. Hazra, S. W. Sharshir, R. Prabakaran, S. C. Kim, S. Panchal and H. M. Ali, "A State-of-the Art Review on Advancing Battery Thermal Management Systems for Fast-charging”, *Applied Thermal Engineering*, Vol. 226, 120303, 25 May 2023.

(4) A. Wray and K. Ebrahimi, “Octovalve Thermal Management Control for Electric Vehicle”, *Energies*, 15(17), 6118, 2002.

(5) N. Kunimine and A. Nakamura, *Thermal Design and Numerical Simulation*, Ohmsha, Ltd., 2015.