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Keywords: Electric vehicle, Automatic air-conditioning system, Battery temperature variation

Abstract. In the present electric or hybrid vehicle, a PTC heater is adopted to provide heating function. In order to overcome the drawback of low efficiency of the PTC heater, a modified heat pump system structure was proposed to recover the waste heat which is generated by the subsystems of the electric vehicle. The recovered heat is transferred by the refrigerant and used to heat up the air that enters the cabin. In this paper, the electric vehicle battery pack is chosen as the target subsystem. A battery cell model was coded on the SC/Tetra platform and corrected according to the experiment data. The simulation results showed that the maximum heat generated by the battery modules (176 cells) under 1.5C discharging is about 356 W which could reduce 20% of the heat absorbed from the environment if a complete battery pack (400 cells) is used.

Introduction

Air-conditioning system is one of the important accessory systems of electric vehicle (EV) which provides a comfortable cabin environment to the passengers. In the present electric or hybrid vehicle, an electric compressor and a PTC heater are adopted to provide cooling and heating function.

The refrigerant is compressed by the electric compressor and absorbs the heat inside the cabin to decrease the temperature. The electric compressor is able to vary the rotational speed according to the heat load of the cabin. Therefore, the efficiency of the cooling subsystem is able to increase by reducing the unnecessary electric energy. The PTC heater generates heat by consuming electricity to heat-up the medium which is usually air or water. The medium is then used to warm up the air that enters the cabin by a heat exchanger. Although the PTC heater could provide sufficient heat energy to warm up the cabin, low energy efficiency is presented due to the complex heat transfer mechanisms. According to research of the electric vehicle manufacturer, the use of the PTC heater reduces the electric vehicle mileage from 50% to 70% where the electric compressor is from 30% to 50% [1]. Therefore, a solution which could provide high efficiency heating function is needed. In 2010, a modified heat pump system structure was presented by Automotive Research & Testing Center (ARTC). The modified structure could recover the heat generated from the EV subsystems and uses to heat up the cabin.

In this paper, the battery pack used in the ARTC electric vehicle is chosen as the subsystem. The maximum heat which can be recovered by the proposed system is simulated to study the feasibility of the modified heat pump system.

Modified Heat Pump System Structure

Heat pump system is a well-developed technology and a lot of products have been designed based on this technology. The system retrieves heat energy from the environment and heats up the indoor space. However, some of the characteristics of the heat pump system make it hard to use in the vehicle, i.e. low heat absorption and frosting of condenser under extremely weather condition. Therefore, additional heat sources are needed to overcome these drawbacks. Since the subsystems of the EV generate heat during operating, they could be used as the heat sources to the heat pump system.

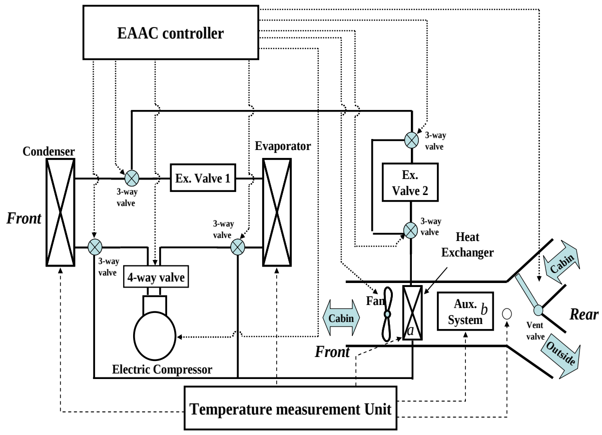

Fig. 1. ARTC modified heat pump system structure

Fig. 1 shows the modified air-conditioning/heating system structure diagram. An additional heat exchanger (HE), an expansion valve (EXV), several check valves and solenoid valves are added into the original air-conditioning system. During the heat pump system operates, the fan draws the air to flow through the subsystem to take away the generated heat. The air then passes the HE which is placed adjacent to the subsystem to transfer the heat to the refrigerant. The refrigerant with additional heat then flows into the evaporator to heat up air which enters the cabin. Therefore, the heat energy which is absorbed from the environment could be reduced.

Li-ion Battery Heat Generating Model

The subsystems on the electric vehicle, i.e. propulsion motor, inverter and battery pack, generate heat during operating. The heat generated by these subsystems usually dissipates by the air-cooling or liquid-cooling mechanism. Among those subsystems, the efficiency of the battery is highly sensitive to its temperature. The battery efficiency will decrease whether at high or low temperature. Therefore, the temperature of the battery is needed to be controlled within a proper range. In other words, the heat generated during operating is needed to be removed to control the temperature. In this study, the battery pack was chosen as the target subsystem to study the heat generated during discharging.

In order to simulate the battery temperature behavior during discharging, the heat generating mechanism is needed to study. In the research of Li-ion battery temperature variation [2], three types of the heat generation are modeled respectively. During the discharging, the reaction heat which is the sum of the heat generated at both positive and negative pole is derived as

$$Q_{reac} = Q / F \times I = 0.0104QI \tag{1}$$

where Q is the sum of the heat generated at both the negative and positive pole, F is the Faradays constant and I is the discharging current. The heat generated by the internal and polarization resistance of the battery can be expressed as Eq. 2 and Eq. 3

$$Q_{ploar} = I^2 R_{pd} \tag{2}$$

$$Q_{\text{int}\,er} = I^2 R_e \tag{3}$$

where R_{pd} is the polarization resistance and R_e is the internal resistance of the cell. Therefore, the overall heat generated during discharging is the sum of Eq. 1 to Eq. 3 which is derived as

$$\begin{aligned} Q_z &= Q_{reac} + Q_{polar} + Q_{\text{int}\,er} = Q_{reac} + I^2 R_{pd} + I^2 R_e \\ &= 0.0104QI + I^2 R_{td} \end{aligned} \tag{4}$$

where R_{td} is the sum of the internal and polarization resistance.

Simulation and Experiment Results and Discussion

In this paper, the Finite-Volume-Method (FVM) was adopted to simulate the battery temperature variation behavior. The heat generated during discharging, as shown in Eq. 4, was used as the boundary condition of the simulation. The battery cell models were built and coded in the SC/Tetra software with 400k grids. The model of the battery module, which includes 16 cells as shown in the figure, was built based on the cell model. Therefore, the number of the grids of the battery module is 6.3 million.

In order to obtain an accurate simulation result of the battery pack temperature and the generated heat, several experiments were executed to obtain the temperature behavior of the battery cell and module. The experiment conditions are listed in Table 1. Each experiment was repeated for three times to obtain an arithmetic average result of the cell and module temperature. The experiment data was then used to correct the model of the battery cell and module.

Table 1 Discharging Experiment Conditions

	Capacity	Volt.	Discharging Current	Discharging Period
Cell	15Ah	3.2V	15A (1C)	15 min
			22.5A (1.5C)	10 min
Module	60Ah	3.2V	60A (1C)	15 min
			90A (1.5C)	10 min

Experiment and simulation of cell and module temperature. Fig. 2 shows the experiment and corrected simulation results of the single cell temperature variation under 1C and 1.5C discharging. The experiment data start from different values due to the different environment temperature when the experiment is executed. However, the experiment results show a similar temperature increasing tendency. As shown in Fig. 2(a), all the experiment data shows that the cell temperature all increases 2.7℃ under different initial temperature and the simulation result shows the same temperature increasing magnitude. Furthermore, the experiment results show that the cell temperature increases with a smoother slope before 300 seconds which is different from the simulation result. Due to the in-uniform thermal resistance of the battery cell, the temperature of the cell surface will be increase d slower than in the core.

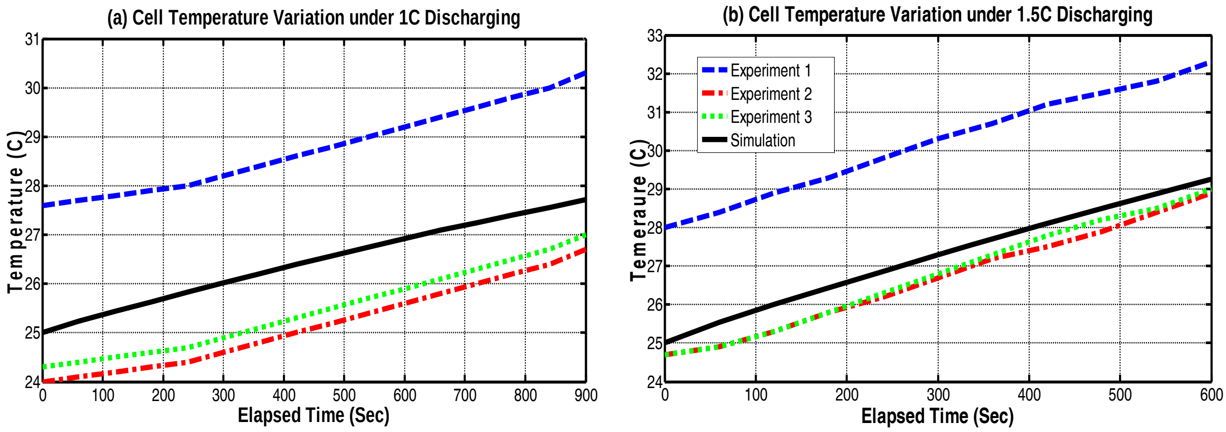

Fig.2. Cell temperature variation under (a) 1C and (b) 1.5C discharging

Fig. 2(b) shows the temperature variation of the cell under 1.5C discharging. The experiment and the simulation results show the similar temperature increasing magnitude of 4.3℃. In addition, the experiment cell temperature increases with a constant slope which is different from the results with 1C discharging. Since the heat generated under 1.5C is higher than under 1C, it takes shorter time to increase the cell temperature.

Fig.3 shows the cell temperature of the battery module under discharging. It can be seen that the temperatures of the cells are different. The cell which is the output joint of the module will have a higher temperature than the other cells due to the maximum current loading. Since the temperatures of the cells in the module are different, an arithmetic average of the cell temperatures is used to represent the overall module temperature. Therefore, the simulated module temperature is also an arithmetic average of the cell temperatures.

Fig. 4 shows the temperature variation of the module under 1C and 1.5C. The initial module temperature is the environment temperature when the experiment is executed. It can be seen that the module temperature increases 4.6℃ and 6.4℃ respectively. The simulation results show similar temperature increasing tendency to the experiment result.

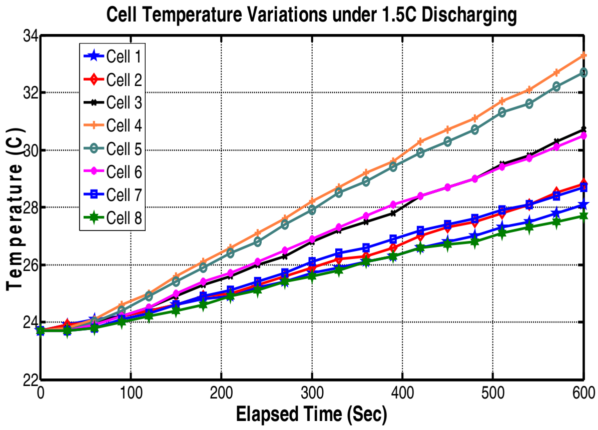

Fig.3. Cell temperature variation in a module

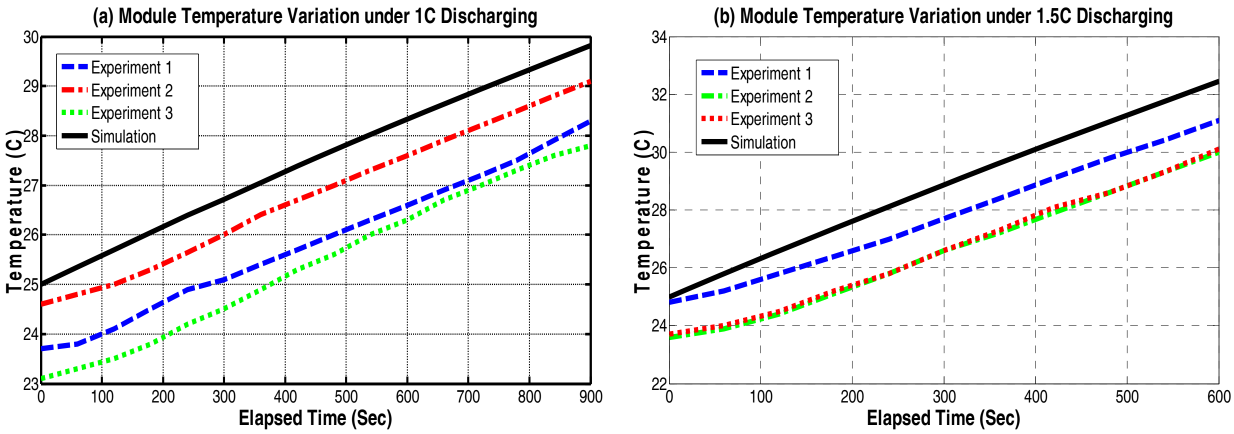

Fig.4. Module temperature variation under (a)1C and (b) 1.5C discharging

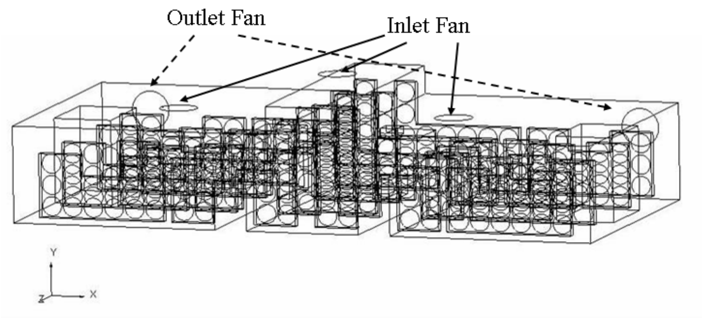

Fig.5. Battery stack model

Simulation result of battery pack heat generation. The simulation results show that the model of the battery cell and module have an accurate results in compare with the experiment. Therefore, the model is reliable to simulate the temperature behavior of the battery pack. There are totally 400 cells in the ARTC electric vehicle battery pack. However, only part of the battery pack is able to be simulated due to the limitation of computer hardware. Fig. 5 shows the diagram of the battery pack which includes 11 modules, i.e. 176 cells. The pack model is built based on the correcting cell model and the number of the grids of the model is 74 million. There are three fans that drag the air into the pack from the top side, i.e. +y direction, and two fans that draw the air outside the pack in the –z direction.

The battery pack model is then used to simulate the pack temperature and the maximum heat that could be took out by the outlet fan. With the initial condition of environment temperature (25℃) and 1.5C (90A) discharging current, four temperature profiles with different layer of cells in the pack at the 600 second is shown in the right hand side of Fig. 6. It can be seen that the cells which are close to the fans, whether inlet or outlet, have a lower temperature than other cells. Furthermore, the cells at the higher layer also show a lower temperature than at the lower layer. Due to the alignment of the cell in the battery pack, a non-uniform temperature distribution is shown in the figure.

The left hand side of Fig. 6 shows the air flow field diagram of the pack. It can be seen that the air velocity in the channel which is beneath the inlet fan is higher than other place. In other words, only the heat generated by the cells which is beneath the fans could be easily removed. Part of the heat generated by other cells will remain in the pack and increase the pack temperature. The simulation result shows that the maximum temperature in the pack is 34.8℃ which is 9.8℃ higher than the environment.

According the battery pack simulation result, it shows that the heat which could be removed by the outlet fan is 356W. Therefore, the heat recovered from the overall ARTC EV battery is estimated to be 809.09W which is nearly 20% of the heat energy needed for a sedan heating function.

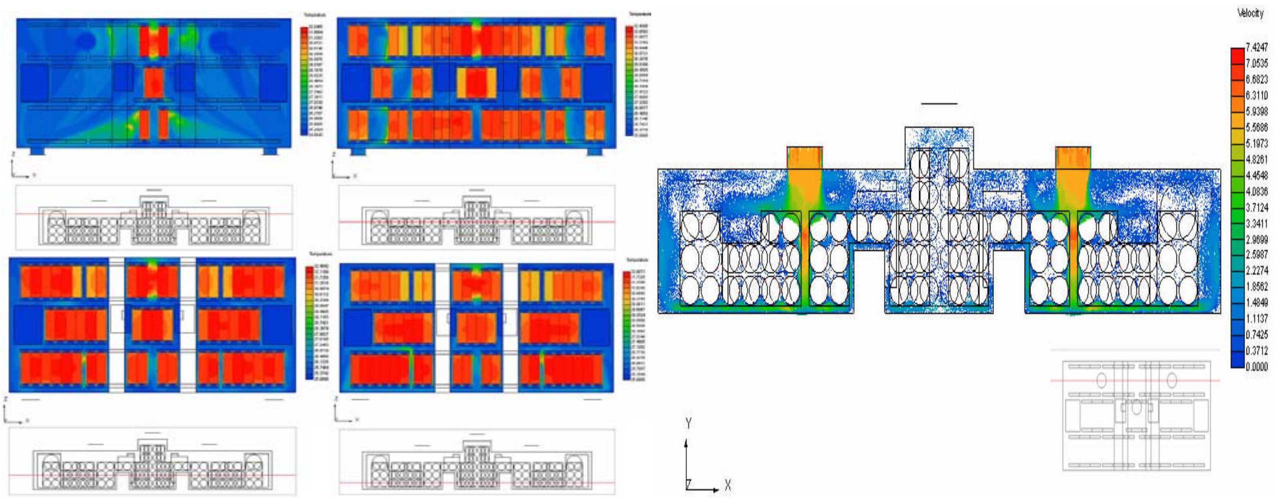

Fig.6. Temperature profile and air velocity distribution of the battery pack

Conclusions

In this paper, the temperature variation and generated heat of the electric vehicle battery during discharging was studied. The models for the battery were coded on the SC/Tetra platform and the Finite Volume Method was used to simulate the behavior of the model. Several experiments were executed with two different discharging currents for the temperature of the cell and the module. The results were then used to correct the simulation models. The modified model shows good results for the temperature behavior in compare with the experiments. The simulation results of the battery pack shows that the maximum heat energy which is possible to be recovered is 809.09W which is nearly 20% of the heat energy for the heating function. Therefore, the modified heat pump system may provide a sufficient heating function for the EV under cold weather.

References

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