Control Strategy of Coolant Flow Rate and Temperature of Battery Pack Based on Double Fuzzy Controller

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Abstract. The temperature and flow rate of coolant have a great influence on the performance of the cooling system. Too low temperature of coolant will increase the temperature difference between single batteries, and too high temperature will not be conducive to battery cooling. If the flow rate of coolant is too high, it will lead to the increase of system energy consumption and reduce the vehicle's mileage, but too low flow rate of coolant will lead to the increase of battery temperature, which will bring safety risks. In order to solve these problems, this paper takes both the maximum temperature and the maximum temperature difference of the battery into consideration and proposes a double fuzzy controller. Compared with the step control scheme, the maximum temperature is reduced by 3 ℃, and the maximum temperature difference is reduced by 1.75 ℃, and the energy consumption is reduced by 13.3%.

1. Introduction

In the research of liquid cooling and heat management, some scholars have studied the influence of coolant materials on cooling effect [1,2]. Some parts of the researchers have studied the influence of the shape and structure of the cold pipe on the cooling effect [3,4]. In addition, some scholars have carried out research on cooling effect optimization [5], which is also the main work of this paper.

Some studies have shown that, under the same conditions, reducing the inlet temperature of the module coolant can reduce the temperature rise of the battery, but it will cause the temperature difference between the cells to increase [6]. Increasing the coolant flow rate can not only effectively reduce the temperature rise of the battery, but also reduce the maximum temperature difference between the cells [7]. Therefore, before controlling the coolant, we should firstly adjust the temperature of the coolant. If the flow rate cannot meet the cooling requirements of the battery pack within the flow rate regulation range, then adjust the coolant temperature to meet the cooling requirements of the battery pack. The optimal working temperature of lithium-ion battery is 20 ~ 40 ℃, and the temperature difference between cells is often required to be controlled within 5 ℃ in the design of battery pack. Therefore, 35 ℃ is set as the standard value of the maximum temperature
of battery in this paper. The control standard of the cooling system is to control the maximum temperature of the battery at about 35 °C and the temperature difference between the cells at about 5 °C. Some studies have shown that when the temperature of the coolant is about 30 ℃ [8], better cooling effect can be achieved, so the upper limit temperature of the coolant can be set to 30 ℃. If the ambient temperature is lower than 30 ℃, the temperature of the coolant can be set to the ambient temperature.

2. Design of the controller for regulating the flow rate of coolant

2.1. Design of controller based on maximum temperature

In the process of battery pack design of pure electric vehicle, the maximum temperature standard of battery is generally set at 35 ℃. Therefore, in the design of flow rate regulation controller based on the maximum temperature, the difference $e_1$ between the maximum temperature of module and 35 ℃ and the change rate $e_{c1}$ of difference can be used as the input of fuzzy controller, and the flow rate regulation $v_1$ can be used as the output. As the lower limit of the battery temperature of the regulation system is 20 ℃, the temperature range of the battery is taken as 20 ℃ ~ 50 ℃. So the basic field of error $e_1$ is [-15,15], and the basic field of error change rate $e_{c1}$ is [-3,3], and the basic field of flow rate $v_1$ is [-0.3,0.3]. If $v_1$ is negative, it means to reduce the coolant flow rate, and if $v_1$ is positive, it means to increase the coolant flow rate. The fuzzy parameters of the input and output of the controller are shown in Table 1.

Table 1. Fuzzy Parameters of input and output.

|       | $e_1$ | $e_{c1}$ | $v_1$ |
|-------|-------|----------|-------|
| Basic field | [-15,15] | [-3,3] | [-0.3,0.3] |
| Quantization field | $E_1 = \{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$ | $E_{c1} = \{-6, -5, -4, -3, -2, 0, 1, 2, 3, 4, 5, 6\}$ | $V_1 = \{-6, -5, -4, -3, -2, 0, 1, 2, 3, 4, 5, 6\}$ |
| Quantization factor | $K_{e_1} = 0.4$ | $K_{e_{c1}} = 2$ | $K_{v_1} = 20$ |
| Fuzzy word set | NB, NM, NS, ZO, PS, PM, PB |

Select the triangle membership function as $e_1$, $e_{c1}$, $v_1$ membership function, and use the fuzzy control module in MATLAB to draw $e_1$, $e_{c1}$, $v_1$ membership function diagram, as shown in Figure 1.

According to the literature research and simulation experience, there is such a relationship between the coolant flow rate and the maximum temperature of the battery: when the maximum temperature of the battery is higher than 35 ℃, the coolant flow rate needs to be increased, and the larger the difference is, the faster the flow rate is. When the maximum temperature of the battery is lower than 35 ℃, the coolant flow rate needs to be reduced, and the larger the difference is, the slower the flow rate is. Based on this control experience, table 2 is formulated According to the fuzzy control rule table, the output of the fuzzy control rule is the fuzzy quantity. In order to get the accurate control quantity, the center of gravity method is used to defuzzy.
2.2. The design of flow rate adjusting controller based on the maximum temperature difference

Generally, the maximum temperature difference of the cell in the battery module is within 5 ℃, so the input of the fuzzy controller is the difference between the maximum temperature difference between the cell and 5 ℃ and the change rate of the difference $e_{c2}$. The output is the flow rate regulation $v_2$. $v_2$ is negative to reduce the flow rate of the coolant and positive to increase the flow rate of the coolant. The input and output fuzzy parameters of the controller are shown in Table 3. We can get the membership function graph of $e_2$, $e_{c2}$, $v_2$ and fuzzy rule table of $v_2$ by using the method mentioned in subsection 2.1.

Table 2. Fuzzy rules of $v_2$

| $v_2$ | $e_1$ | $e_{c1}$ |
|-------|------|--------|
| NB    | NB   | NB     |
| NM    | NB   | NM     |
| NS    | NM   | NS     |
| ZO    | NS   | ZO     |
| PS    | NS   | PS     |
| PM    | NS   | PM     |
| PB    | ZO   | PM     |

Table 3. Fuzzy parameters of input and output.

| $e_2$ | $e_{c2}$ | $v_2$ |
|-------|---------|-------|
| [-5, 5] | [-1.5, 1.5] | [-0.3, 0.3] |

3. Control effect of flow rate

3.1. The design of flow rate adjusting controller based on the maximum temperature difference

Figure 3 shows the Simulink model of the flow rate control of the battery pack. The model input is the output voltage, current, load factor $K$, coolant temperature regulation $dT$, ambient temperature $T$ and cycle number $N$ of the battery pack. The output is the coolant temperature regulation and the actual power of the coolant pump. The load factor $K$ is the ratio of the actual power of the water pump to the output power of the battery pack, which will be adjusted according to the maximum flow demand of the 16 battery modules during the operation; the coolant temperature regulation $dT$ is the maximum value of the regulation demand of each module, and the positive $dT$ is the need to reduce the coolant temperature.

3.2. Simulation verification

In order to verify the control effect and relative advantage of the flow control scheme, this paper will test the control effect of the flow control scheme and the hierarchical control scheme proposed in this paper, using the flow control model of battery pack and fluent as the test platform respectively. The maximum temperature, maximum temperature difference and flow rate curve of the battery module are obtained by sorting out the temperature and flow rate data of the two different simulation platforms, as shown from Figure 2 to Figure 4.
It can be seen from Figure 2 to Figure 4 that the flow control scheme proposed in this paper can control the maximum temperature of the battery around 35 °C and the maximum temperature difference around 5 °C, but the maximum temperature and the maximum temperature difference of the battery in the early stage of the test are higher than the maximum temperature and the maximum temperature difference under the step control scheme, mainly because the coolant flow rate in this stage is lower than that under the step control scheme. However, with the increase of discharge current in the later stage of the test, the flow rate control scheme proposed in this paper can quickly adjust the coolant flow rate and control the maximum temperature and temperature difference of the battery near the standard value, while the hierarchical control scheme cannot adjust the coolant flow rate in time, which results in the rapid rise of the maximum temperature and temperature difference of the battery. The cooling effect comparison between this paper and the step control scheme is shown in Table 4.

Table 4. Comparison of cooling effect under different regulation schemes

| Scheme of this paper | Step control scheme | Optimization value |
|----------------------|---------------------|--------------------|
| Maximum temperature  | 35.3°C              | 38.3°C             | 3°C                |
| Maximum temperature  | 5.2°C               | 6.95°C             | 1.75°C             |
| difference           |                     |                    |
| Energy consumption   | 40.24KJ             | 45.48KJ            | 13.3%              |
4. Conclusion
In order to realize the efficient cooling of the battery pack cooling system, this paper proposes the flow rate and coolant temperature control scheme based on the double paste controller, and builds the Simulink verification platform model, and then tests the flow rate control scheme and the step control scheme in the verification platform model and fluent respectively. The test results show that under the same input conditions, the flow rate control scheme proposed in this paper reduces the maximum temperature of the battery to 35.3 ℃ and the maximum temperature difference to 5.2 ℃. Compared with the temperature step control scheme, the maximum temperature is reduced by 3 ℃ and the maximum temperature difference is reduced by 1.75 ℃. The energy consumption of the whole test process is also reduced by 13.3%.

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