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Research Paper

Orthogonal experimental design of liquid-cooling structure on the cooling effect of a liquid-cooled battery thermal management system

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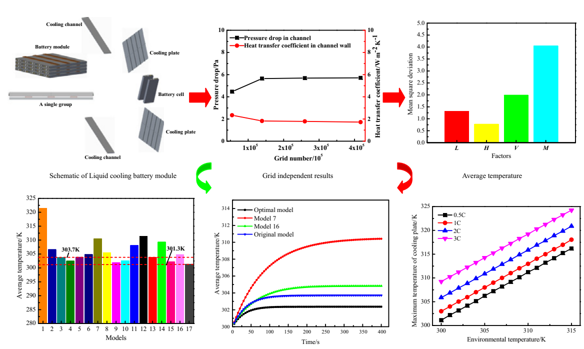
HIGHLIGHTS

- A $L_{16}(44)$ orthogonal array is selected to design sixteen models.
- Cooling effect of a liquid-cooled battery thermal management model is investigated.
- Number of the pipe has obvious effect on the average temperature of the cooling plate.
- Optimal case by this orthogonal analysis can meet various cooling conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to analyze the influence of four parameters on the cooling effect of a liquid-cooled battery thermal management model, a $L_{16}(44)$ orthogonal array is selected to design sixteen models to perform and quantify the parametric to identify the main and secondary factors, then the optimal combination model is found. The results show that the number of the pipe has most obvious effect on the average temperature of the cooling plate in the four parameters, and velocity of coolant flow is second, pipe height has the minimal effect. In terms of temperature uniformity, amount of pipe and velocity of coolant have similar effects which are both main factors, pipe width and pipe height have similar effects which are both secondary factors. The optimal case by this orthogonal analysis can meet various cooling conditions.

1. Introduction

Currently, there has been a great efforts in internal purification technology (Partially Premixed Compression Ignition(PPCI) [1], Reactivity Controlled Compression Ignition (RCCI) [2], Exhaust Gas Recirculation (EGR) [3–4], turbocharger [5], cold start control strategy [6], etc.), aftertreatment technology [7–11] and renewable

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alternative fuels such as biodiesel [12–15] that can reduce some pollutions of auto emissions. But how to control the auto emissions from the root is still a hard task.

Therefore, more and more attentions had been paid on the development of new energy electric vehicle industry [16–18] included hybrid electric vehicles (HEVs) and electric vehicles (EVs). It's well known that a common core component in hybrid electric vehicles (HEVs) and electric vehicles (EVs) was power battery pack. Power battery pack's performance and life cycle were particularly important for vehicle safety and performance [19,20]. Keep it working at a reasonable temperature range was the critical condition to guarantee the performance of power battery [21]. Hence, an efficient battery thermal management system was usually essential [22,23]. Keep battery pack working in a particular temperature range and a small temperature difference can be obtained by a reasonable battery thermal management system [24,25]. That's the meaning that the temperature of the system was between 25 °C and 40 °C and distribution was less than 5 °C from different batteries [26].

In international, the first paper in battery thermal management research fields was about using phase change material (PCM) to manage the temperature of power system [24] and PCM cooling technology [27,28] had been used for some different applications such as building energy conservation and battery thermal management [29,30]. An in-depth study of battery thermal management was showed by Rao et al. [17,19,20]. According to the classification of cooling medium, the most common battery thermal management system mainly included three kinds: air cooling [22], liquid cooling [31,32] and phase change materials [33] at present. As for the battery pack working at a high charge or discharge rate with great heat production, the liquid-cooling showed very obvious advantages [34]. Pesaran [35] made an experimental comparison of the performance of liquid cooling versus air cooling, the results indicated that the maximum temperatures of system was much higher than liquid when air was used as the heat transfer medium. The liquid cooling system of silicone dielectric coolant was proposed by Nelson et al. [36], the experiment results showed that whether heating or cooling, the liquid-cooling system was more efficiency than air cooling. Better thermal balance and uniformity could be achieved by the use of liquid cooling when the Ni-Cd battery module charged and discharged in the high rate [37]. Several snake-type liquid-cooling plate structures were designed for optimizations of the channel structure, the results showed that the temperature consistency was improved and the pressure drop was reduced of cooling liquid [25]. The UDF function defined the battery heat model was used by Nieto et al. [24] and the results showed that the battery maximum temperature was lower than 35 °C when the cooling water flow at 2.375 L/min. A liquid cooling plate structure with fin (liquid cold plate) was proposed by Jin et al. [38], the results showed that the surface temperature of the heater was dropped with the decrease of the fin spacing and the increase of flow rate of the coolant circulating through the cooled plate. The higher coolant flow rate and larger cooling plate thickness were helpful for the battery group maintained at low and good uniformity temperature were found by Tong et al. [39]. A mini-channel cold plate-based battery thermal management system was used to cool a rectangular Li-ion battery which was designed by Huo et al. [19], numerical calculation showed that the number of pipes, the velocity of cooling fluid had obviously effect on the maximum temperature of the system. The energy density of power batteries was high, the most effective thermal management was provided by a liquid cooling system [40,41].

Based on the above literature review, it's well known that structure optimizations of battery thermal management system were mainly to change one parameter of structure. Since the combinations of the parameters and variables are too many, it's taken a lot of time and effort to investigate the systems with multiple interact parameters, it is urgent to find a research method which can save time and cost for the investigation.

In this work, a numerical study of a power battery thermal management with rectangular channels and cold plate is presented and the influence of the four factors (namely channel width, channel height, amount of pipe and velocity of coolant) on heat dissipation is simulated and analyzed by changing four parameters. Be different from previous works, the objective of this work is finding out the influence of four parameters on the cooling effect of a liquid-cooled battery thermal management model. In order to find out the impact of these parameters and the optimal structural parameter, all factor and level combinations are needed to be analyzed and investigated. A large number of experiments and analysis are required with conventional testing approach. For instance, four factors are involved in the system that can be divided into four continuous levels, corresponding to 4^4(256) different possible combinations of factors and levels, then 256 conditions have been investigated, a lot of time and money is needed. Hence, an effective parametric study method for reducing the number of cases and saving computational time is needed to arrange tests.

Orthogonal experimental design [42] is a widely used multifactor experimental method based on orthogonal array, and the results of orthogonal experimental design can meet the requirements of comprehensive test. Therefore, the orthogonal experimental design method is adopted to investigate the optimal structural parameter of the liquid cooled battery thermal management system in this paper which is never used in published papers. According to related factors and levels, $L_{16}(4^4)$ orthogonal arrays are used to study quantization parameters. Orthogonal arrays of the sixteen cases are selected with different geometry settings and the same results for the 256 conditions can be obtained by the investigations of the sixteen cases in Orthogonal array. In this work, the comprehensive influence of multi variables (channel width, channel height, amount of pipe and velocity of coolant) on the cooling effect of battery thermal management system is studied by the new method of orthogonal experiment with less time and costs. Then the optimum battery thermal management system is obtained under different combinations of parameters, providing us great reference value for further improving the working performance of the battery thermal management system.

2. Initial cooling model and orthogonal design

2.1. Numerical model

A power battery thermal management with rectangular channels and cold plate is presented in this paper. Some rectangular straight channels are arranged in the interlayer of two cold plates for the cooling liquid circulation passage. A single group consists of ten battery cells, two cooling plates and two sets cooling channels. Batteries are sandwiched between the two cooling plates, the other sides of the cooling plates are cooling channels which are used for the next group also. The schematic of the Li-ion battery module is shown in Fig. 1, it consists of a series of cold plates, batteries and rectangular tubes arranged alternately.

The batteries in each layer of the module are in 2 rows and 5 columns. Initial geometrical parameters of the module are denoted in the form of capital letters, and these parameters are fixed. The length of cooling plate is 554 mm, the width of cooling plate is 520 mm and the thickness of cooling plate is 1 mm. The length, width and thickness of initial rectangular channel are 554 mm, 520 mm and 1 mm respectively. The number of channels is 4, the velocity of coolant is 0.05 m/s.

In this paper, the cold plate is assumed to be homogenous and isotropic for numerical simplicity. Aluminum is used for the cold