

Optimal design of combined cooling structure for Lithium-Ion battery in Energy Storage Device

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Batteries are the essential elements in energy storage devices. Thermal control of batteries is imperative to safely operating energy storage devices. To decrease the maximum temperature and reduce the temperature difference inside the lithium-ion batteries, a cooling system combined with air and plate-fin cooling is proposed and optimized. A novel structure of plate-fin is designed to promote cooling efficiency. To speed up the optimal design of the combined cooling system, global and local searching algorithms based on the random forest method and Kriging surrogate model are introduced. A battery pack containing eight battery cells is used to test the proposed cooling strategy. The numerical results demonstrate that the optimized cooling method can decrease the maximum temperature and temperature difference of the battery cells and the global and local searching algorithm is an efficient tool for designing battery cooling systems.

Index Terms—structure optimization, Kriging surrogate model, random forest model, thermal analysis.

I. INTRODUCTION

Lithium-ion (Li-ion) battery is the most widely adopted due to its high energy density and long life cycle. However, Li-ion battery generates vast quantities of heat during the circulatory charging and discharging process. When the operating temperature exceeds an appropriate range, the performance and lifespan of the Li-ion battery are deteriorated severely. In some extreme cases, a thermal runaway may happen. Therefore, it is crucial to propose an effective and efficient battery cooling structure for the safe and optimal operation of the energy storage device.

Due to its necessity and importance, the cooling structure has become the hot spot of Li-ion battery energy storage devices[1]-[3]. The current cooling schemes can be mainly categorized as natural or forced convection, liquid cooling, phase change material cooling, and heat sink. Due to the simplicity of design and low cost, air cooling systems continue to be widely employed in Battery thermal management system[4]. However, natural or forced convection cooling suffers from poor heat dissipation efficiency. Furthermore, a sole cooling scheme cannot always satisfy the demand for fast heat dissipation in high-capacity energy storage device. In this regard, a combined cooling structure based on forced convection and a finned heat sink is designed and optimized.

II. COMBINED COOLING STRUCTURE BASED ON FORCED CONVECTION AND FINNED HEAT SINK

To increase the heat dissipation capacity, a novel structure of fin is proposed. To maximize the effect of the combined cooling structure, an optimization algorithm based on the random forest method and a Kriging surrogate model is developed.

A. Novel Fin Structure

A longitudinal plate is one of the most commonly used fin configurations. To enhance the ability of heat transfer, the

surface of heat dissipation is increased by adding small wings on the fin. Figure 1 gives the proposed structure of the finned heat sink. In Figure 1, the grey part is the original longitudinal-plate finned heat sink and the blue part is proposed "small wings" to promote the heat dissipation efficiency.

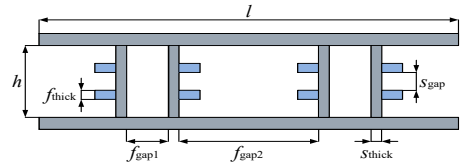


Figure 1 The proposed structure of the finned heat sink

The size of the heat sink is critical to the performance of the Li-ion battery-based energy storage device. If the length and height of the heat sink are too large, it will increase the volume of the energy storage device. If the density of the fins is too high, it may block the air convection to lead to severe temperature differences inside the energy storage device. Therefore, the size of the heat sink needs to be optimized to achieve the optimal cooperation between forced convection and the heat sink. The key parameters of the heat sink are given in Figure 1. In Figure 1, l and h are the length and height of the heat sink, which are associated with the volume of the energy storage device. f_{thick} , f_{gap1} , and f_{gap2} are the thickness of fins and distance between the adjacent fins, which determine the distribution and pattern of the basin fins. S_{thick} , and S_{gap} are the thickness of "wings" and distance between the adjacent "wings", which determine the distribution and pattern of the basin "wings".

B. Optimization Algorithm based on Random Forest and Kriging Surrogate Models

As aforementioned, the size of the heat sink needs to be optimized to obtain a stratified performance. Optimization algorithm iterated with finite element analysis (FEA) is always to solve this optimal design. The temperature FEA of the Li-

ion battery model is a multi-field coupled problem, which is very time-consuming. The time of direct FEA iterations is usually unbearable. Therefore, an improved fireworks algorithm based on Random Forest[5] and the Kriging Surrogate Model[6] is proposed to speed up the convergence. According to the characteristic of the Random forest and the Kriging surrogate model in global and local prediction, Random Forest is used to explore the whole searching space, and the Kriging Surrogate Model is adopted to implement a refined search within the promoting area. The flow chart of the proposed method is given in Figure 2.

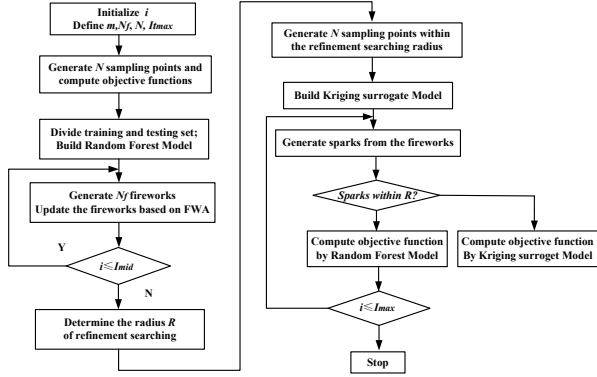


Figure 2. Flow chart of the algorithm based on Random Forest and Kriging surrogate model

The proposed algorithm is given in detail in the following steps:

- 1: **Design of experiment:** generate N initial design points and evaluate them.
- 2: **Initial random forest modeling:** build a random forest model using the data set.
- 3: **Generate fireworks or refine search radius:** if $i \leq l_{mid}$, generate fireworks from Fireworks Algorithm, otherwise refine the search radius R .
- 4: **Initial Kriging surrogate model:** build a Kriging surrogate model from new N sampling points.
- 5: **while** $i \leq l_{max}$ **do**
- 6: Generate sparks from the fireworks.
- 7: Determine if the spark is within the radius, if so, use the random forest model to compute the target value, otherwise use the Kriging model to calculate.
- 8: **end while**

III. COOLING STRUCTURE OPTIMAL DESIGN

A Li-ion battery pack with 12 battery cells is studied. The finned heat sink is put between the battery cells and the wind tunnel is in the middle of the battery pack, as shown in Figure 3. The size of the heat sink is optimized to maximize the cooling effect. The variables of this optimal design are the parameters given in Figure 1. Lower temperate and temperate differences are desired within the battery pack.

The thermal distributions within the Li-ion battery pack before and after cooling structure optimization are given in Figure 3. Figure 4 demonstrates the comparison of the max temperature and temperature difference among different

cooling strategies and structures during the charging cycle. TABLE I is the comparison of the max temperature and temperature difference among different cooling structures. In TABLE I, structure 1 is forced convection combined with a finned heat sink, structure 2 is natural convection, structure 3 is a finned heat sink, and structure 4 is forced convection combined with an optimized finned heat sink. From Figure 3, Figure 4, and TABLE I, it is shown that the combined cooling structure has a better cooling effect in decreasing the max temperature; the optimal design can promote the performance of the cooling structure; the proposed combined cooling structure can control the maximum temperature no higher than 40°C.

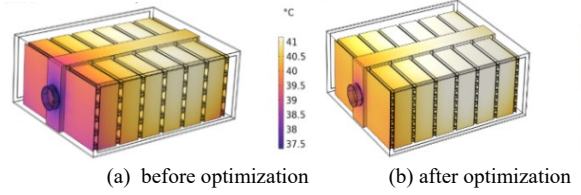


Figure 3. Battery pack simulation results

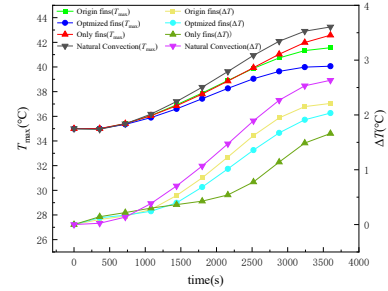


Figure 4. Comparison between different cooling structures

TABLE I
THE RESULTS OF DIFFERENT METHOD

cooling structure	structure 1	structure 2	structure 3	structure 4
$T_{max}(^{\circ}\text{C})$	41.6	43.2	42.1	40.0
$\Delta T(^{\circ}\text{C})$	2.2	3.8	1.3	2.0

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