Research on the thermal protection performance of fireproof and heat-insulating materials with different thicknesses

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Abstract. This study systematically analyzes the protective performance of aerogel thermal insulation materials against the thermal runaway of battery modules through a combination of experiments and numerical simulations. The results show that wrapping with fireproof and thermal insulation materials can significantly reduce the peak temperature of the battery and effectively delay the temperature rise rate for more than 40 minutes. Moreover, increasing the thickness significantly improves the protective effect. The fireproof performance of aerogel is jointly affected by thickness, thermal conductivity, density, and specific heat capacity, among which thickness and thermal conductivity have the most prominent effects. Increasing the number of layers and expanding the gaps between materials can enhance the thermal insulation effect. The results of this study can provide theoretical support and practical reference for the design of battery thermal safety protection.

Keywords: Fireproof and heat-insulating materials; Thermal runaway protection; Thermal conductivity; Numerical simulation.

1. Introduction

The thermal runaway risk of lithium-ion batteries has always been a key challenge restricting their further development and wide application. Effective arrangement of thermal insulation materials is one of the important measures to prevent the spread of thermal runaway. The principle lies in embedding an insulation layer with extremely low thermal conductivity between battery cells to increase thermal resistance[1-3], reduce thermal diffusivity and diffusion speed. The thermal conductivity of insulation materials plays a key role in heat control[4].

Based on the fact that heat transfer through the battery casing is the main cause of propagation[5], inserting a thermal insulation layer can suppress thermal runaway propagation by increasing the thermal resistance between batteries. For example, Larsson et al.[6] used numerical simulations to limit thermal runaway by adding liquid-cooled plates and thermal insulation layers between adjacent batteries. Li et al.[7] designed an intelligent fire wall to suppress the thermal runaway propagation of prismatic battery modules. Lee et al.[3] found that ceramic fiber boards are superior to stainless steel and intumescent materials. Coman et al. [8] used a numerical method coupling thermal and electrochemical models to prove that the air in the pores between the battery and the heat sink acts as thermal insulation to reduce the temperature of adjacent batteries. Additionally, Wilke et al.[9, 10] effectively suppressed the thermal influence of thermal runaway batteries by filling the gaps in a cylindrical 18650 battery pack with phase change materials.

However, the application of thermal insulation layers will reduce the heat dissipation conditions of the battery module, leading to heat accumulation and potentially affecting the normal working performance. Therefore, aerogels are widely used due to their porous structure and low thermal conductivity. For example, Lu[11] compared ceramic fibers, pre-oxidized filaments, and silica aerogels and found that all of them could effectively suppress thermal runaway, with ceramic fibers and pre - oxidized filaments being slightly better. Liu et al.[12-14] studied the thickness and position of aerogel blankets and showed that a 6 mm blanket is cost - effective, a 10 mm blanket has a better heat - blocking effect, and the combined placement at the top and middle has the best performance.

In order to conduct a more in - depth and detailed research and analysis on the prevention and control effect of aerogel fire-resistant and heat-insulating materials on the thermal runaway accidents of ternary lithium - ion batteries, this study combines the protection performance test of fire - resistant and heat - insulating materials with finite element simulation. By analyzing the key characterization data such as the temperature of the fire - facing surface and the back - fire surface of the fire - resistant and heat - insulating materials and the surface temperature of the module, the protection effectiveness of the test object is clarified, providing technical support for formulating corresponding design schemes.

2. Method

2.1 Experiment

In the thermal runaway protection test of the battery module, the battery modules are arranged in a "2+6+2" configuration. During the test, a fireproof and heat-insulating material mainly composed of aerogel was selected to cover the top, bottom, and three sides of individual battery modules, as shown in Fig. 1(a). The thermal parameters of the aerogel material used in this test are shown in Table 1. Two different thicknesses of fireproof and heat-insulating materials, 3 mm and 10 mm, were selected for the test. The water spray intensity of the automatic sprinkler system was 12 L/min/m^2, the battery cabinet doors were all closed, and the number of overcharged batteries was three groups. The thermocouple measurement points and the battery arrangement are shown in Fig. 1(b) - (d).

Table 1. Properties of aerogel materials

Density (kg/m^3)	Specific heat capacity (J/g·℃)	Thermal conductivity						
		25(ºC)	50(ºC)	100(ºC)	200(ºC)	300(ºC)	400(ºC)	500(ºC)
332	1.72	0.025	0.028	0.029	0.035	0.041	0.056	0.069

Fig. 1 Battery layout.(a) The condition of batteries wrapped with fireproof and heat-insulating materials; (b) Schematic diagram of thermocouple measurement points and the location of

overcharged batteries; (c) 10 mm fireproof and heat-insulating material; (d) 3 mm fireproof and heat-insulating material.

2.2 Numerical simulation of the thermal insulation performance

Based on finite element method to establish a model to simulate the temperature field of the steel plate protected by the aerogel fireproof and heat-insulating material under the above test conditions, and explore the influence of the main thermal properties of the heat-insulating material on its fireproof and heat-insulating effect.

The size of the steel plate is 500 mm×500 mm×5 mm, and that of the aerogel is 500 mm×500 mm× （3/10 mm). The geometric model of the test piece is shown in Figure 1.6. The eight - node three - dimensional solid heat transfer element (DC3D8) is used for all element types. Set the relevant parameters of radiation and convection in the finite element model according to the experimental conditions. The contact between the aerogel insulation material and the steel plate adopts the "Tie" method. The boundary conditions of the finite element model are shown in Fig 2. During the finite element calculation, the thermal parameters of the steel plate are taken according to the provisions of Eurocode 4. The thermal parameters of the aerogel insulation material are based on the data provided by the manufacturer: density 332 kg/m^3 , specific heat capacity 1720 J/(kg·°C).

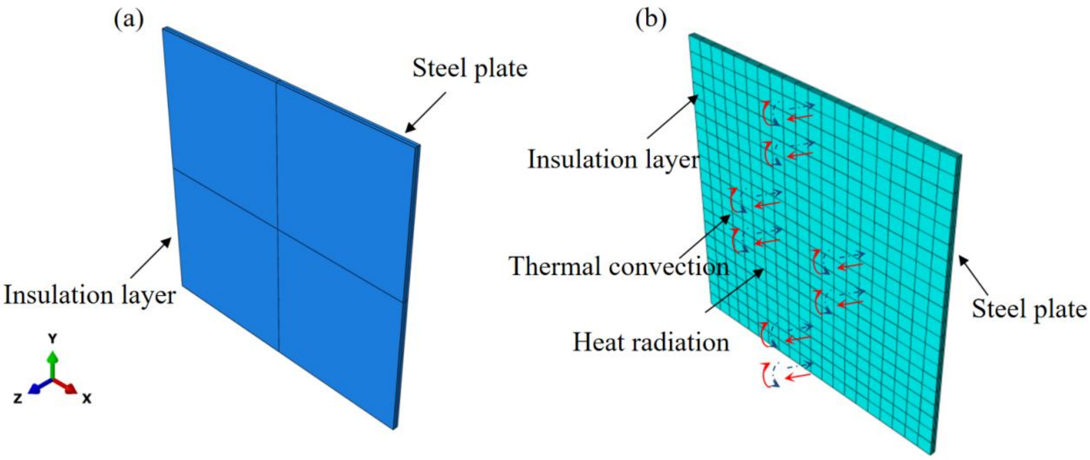

Fig. 2 Setting of model boundary conditions. (a) Establishment of geometric model; (b) Mesh and boundary conditions.

3. Result

3.1 Experiment

Wrapping the battery module with fireproof and heat-insulating materials significantly reduces the temperature peak (Fig. 3). The 3 mm aerogel reduces the peak temperatures inside and outside the interlayer from 709° C to 178° C and from 822° C to 321° C respectively. While the 10 mm aerogel reduces the peak temperature at the same position from 464° C to 60° C (a decrease of 87.1%). The test shows that wrapping with the material effectively delays the temperature rise for more than 40 minutes, and increasing the thickness further reduces the temperature rise. In addition, after the automatic sprinkler system is activated, the temperature drop rate inside the interlayer slows down significantly.

3.2 Experimental verification of simulation results

When the ambient temperature in the test is measured to act for 4000s, the calculated temperature fields of the 3 mm aerogel insulation material and the steel plate are shown in Fig. 4(a). Which can be seen that under the action of the ambient temperature rise curves in the two cases, the measured values are in good agreement with the finite element calculated values in terms of trends, as shown in Figs. 4(b) - (c).

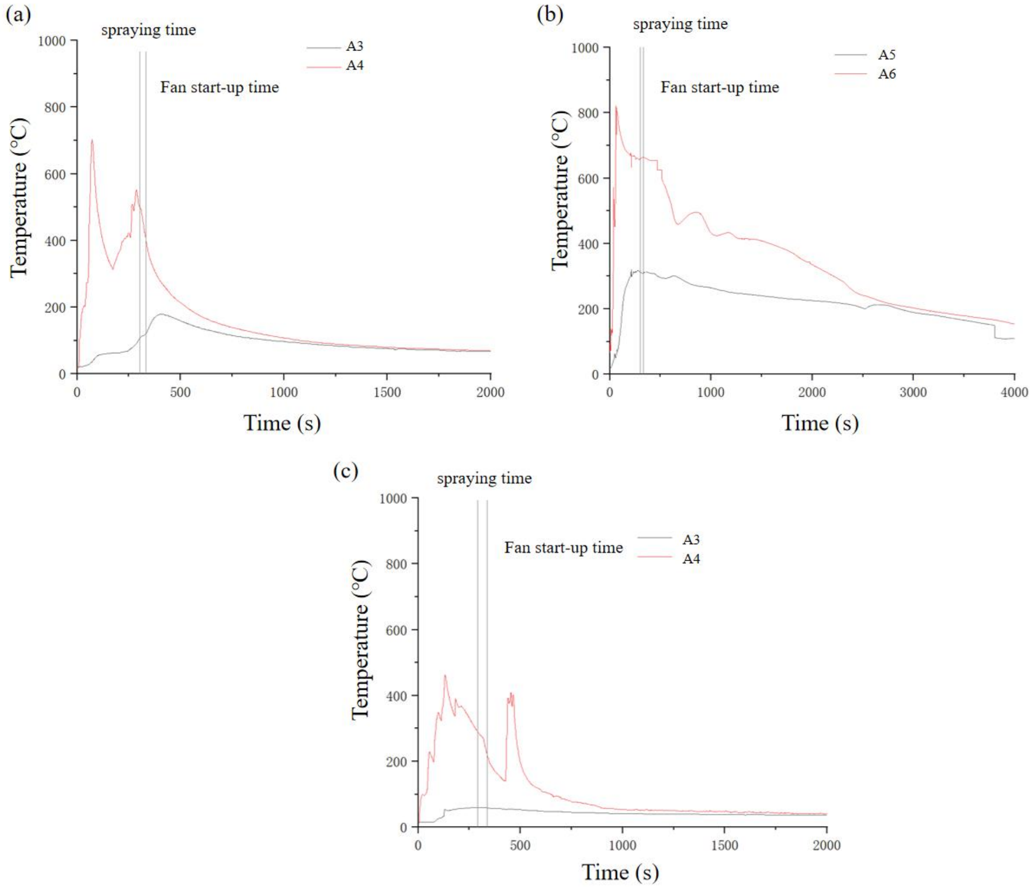

Fig. 3 Comparison of temperatures on the inner and outer sides of fireproof and heat-insulating materials. (a) 3mm (A3\A4); (b) 3mm (A5\A6); (c) 10mm (A3\A4).

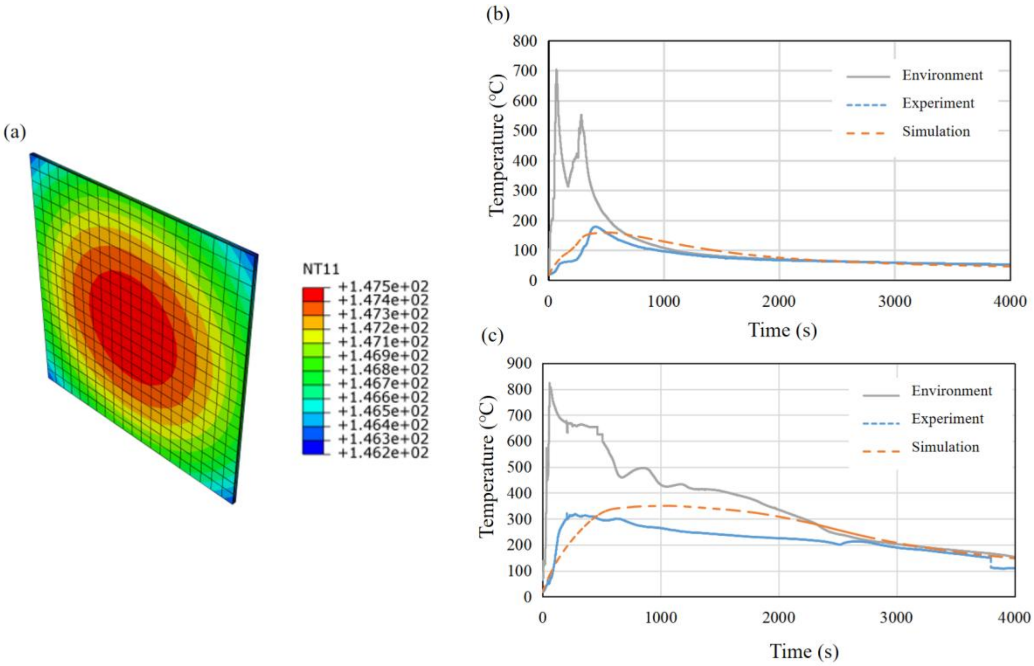

Fig. 4 Temperature-time simulation. (a) Simulated temperature field;
(b) Simulation-versus-experiment comparison for A3/A4; (c) Simulation-versus-experiment comparison for A5/A6.

3.3 Parameter analysis

The results show that the fireproof performance of aerogel insulation materials is affected by multiple parameters: increasing the thickness (Fig. 5a), decreasing the thermal conductivity (Fig. 5b), increasing the density (Fig.5c), and increasing the specific heat capacity (Fig. 5d) can all improve the fire protection effect. Among them, the thickness and thermal conductivity have the most significant influence, followed by the density, and the specific heat capacity has the least influence. Under the condition of the same thickness, increasing the number of layers has a better effect than a single - layer structure, and increasing the gap between the insulation materials can reduce the surface temperature of the protected steel plate (Fig. 5e). In addition, the environmental temperature - rise curve also has a significant impact on the fireproof performance (Fig. 5f).

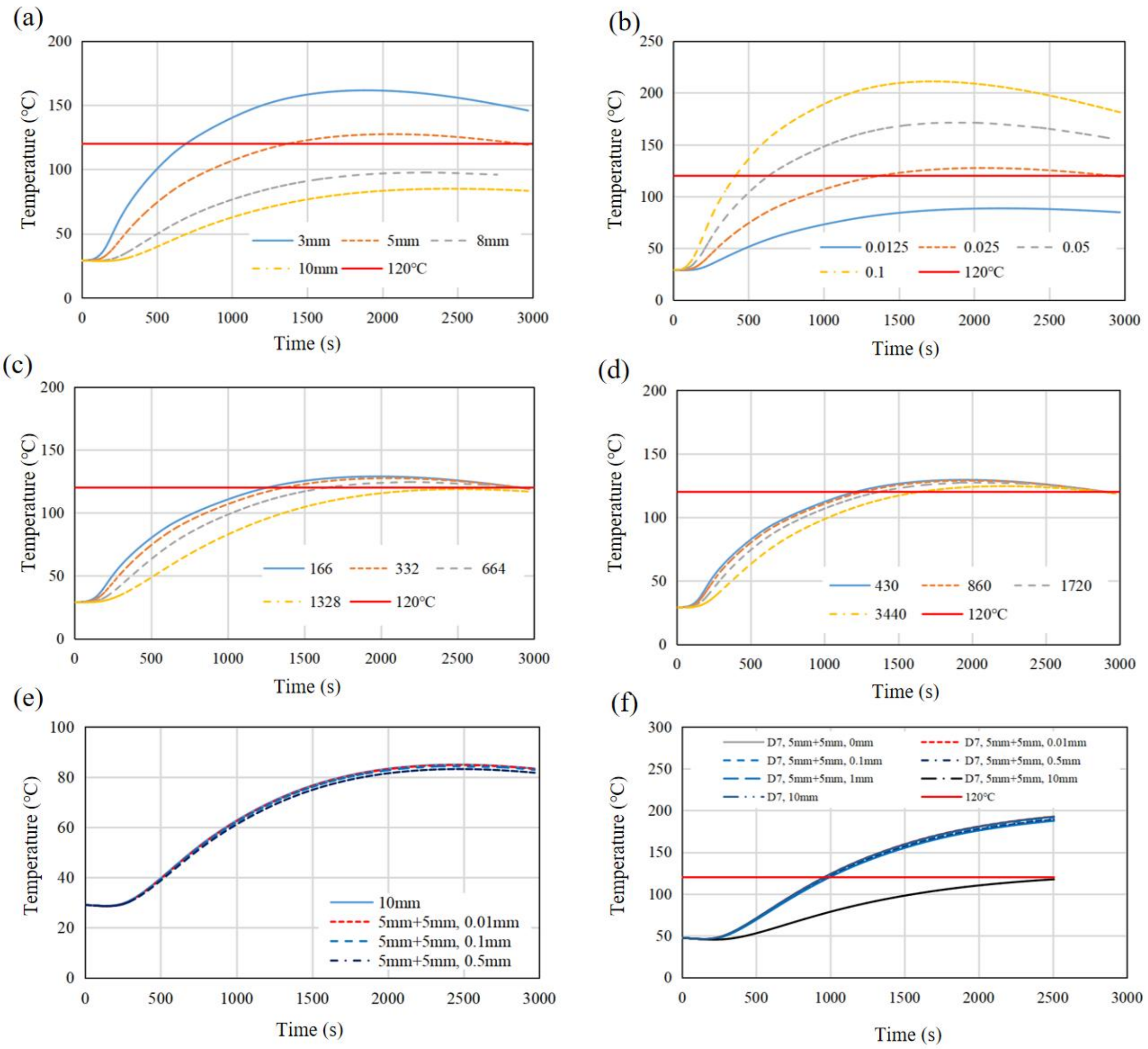

Fig. 5 Effects of key parameters on the fire protection performance of aerogel insulation materials. (a) Thickness; (b) Thermal conductivity; (c) Density; (d) Specific heat capacity; (e) Number of thermal insulation layers; (f) Environment temperature.

4. Conclusion

This study conducted research on the protective effectiveness of fireproof and heat-insulating materials against the thermal runaway of battery modules and the thermal conductivity of fireproof and heat-insulating materials. The results show that wrapping battery modules with fireproof and heat-insulating materials can significantly reduce the influence of external high temperatures and slow down the temperature rise, but it also makes the internal temperature less sensitive to changes in the ambient temperature. Simulating the heat insulation effects such as the temperature rise on the back side of the thermally runaway battery through a numerical model can provide theoretical guidance for the formulation of experimental schemes for battery protection design.

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