Research on Explosion Characteristics of Prefabricated Cabin type Li-ion Battery Energy Storage

Fengbo Tao\textsuperscript{1*}, Kangyong Yin\textsuperscript{1}, Wei Liang\textsuperscript{1}, Haosheng Huang\textsuperscript{1}, Yuandi Lin\textsuperscript{1} and Yuhang Song\textsuperscript{2}

\textsuperscript{1} State Grid Jiangsu Electric Power Co., Ltd. Research Institute, Nanjing, P.R. China
\textsuperscript{2} Zhengzhou University, Zhengzhou, P.R. China
Email: hvtaofb@163.com

Abstract. Lithium iron phosphate batteries have become the main choice for energy storage units in electrochemical energy storage due to their high safety, excellent electrochemical performance, long cycle life, and environmental friendliness. However, lithium-ion batteries inherently have safety risks. The thermal runaway of a single battery in a closed space may cause a chain reaction of surrounding batteries, and may ignite the generated combustible gas, causing serious explosion accidents. In this paper, the explosion characteristics under different initiation points of pressure relief plates are studied. The results show that the peak overpressure variation range of different detonation points in the prefabricated chamber is 1~1.6 times the hatch opening pressure, where the peak overpressure of the detonation at the near end of the hatch is lower than that of the detonation at the distal end, reflecting the role of the detonation when the explosion energy is released to the outside of the chamber earlier. The above study can provide a reference basis for the safe operation of prefabricated cabin type energy storage power plant and the promotion of its application.

Keywords. Lithium iron phosphate battery, initiation point

1. Introduction
Lithium iron phosphate battery [1] has become the main choice of energy storage unit in electrochemical energy storage due to its high safety, excellent electrochemical performance, long cycle life and environmental friendliness [2-4]. In the energy storage system of the power grid, the energy storage unit and electrical equipment are usually unified in the prefabricated cabin, so as to achieve higher capacity, stronger environmental adaptability and ease of installation [5]. However, due to the flammability of the energy storage battery body materials (organic electrolyte, diaphragm, graphite, etc.) [6], there is a risk of battery thermal runaway under abnormal operating conditions [7]. At the same time, because the energy storage prefabricated chamber is relatively confined and the battery stack density in the operating environment is high, the thermal runaway of a single battery may not only cause a chain reaction of surrounding batteries, but also ignite the combustible gas produced by the battery during the thermal runaway process [8], causing an explosion in the space-limited prefabricated chamber [9]. Explosion accidents will not only pose a serious threat to the entire energy storage plant, but will also have a negative negative impact on the promotion of energy storage technology and social evaluation, so in the process of large-scale promotion of electrochemical energy storage projects, the explosion characteristics must be analyzed in the context of the actual working environment of energy storage.
The current research results on the safety of energy storage batteries mainly include the thermal runaway mechanism of energy storage batteries [10,11], the thermal runaway characteristics of cells and small-scale battery modules, and the thermal runaway simulation of battery cells and module modules. On the one hand, due to the limitation of experimental cost and experimental safety, it is mainly concentrated on the smaller-level battery volume, and it is impossible to make a more in-depth analysis of the explosion hazard in the energy storage prefabricated cabin; On the other hand, the way to trigger the thermal runaway of the battery in the experiment is mainly heating, pinning, etc., and there is a big difference between the operation in the real working condition of energy storage, so there is less research related to the gas explosion of prefabricated cabin type lithium-ion battery storage power plant at this stage. Existing energy storage power station safety protection technology is also in the process of gradual improvement, safety protection standards are still in the exploratory stage, and combustion and explosion accidents continue to occur, which severely restricts the promotion and development of energy storage technology. In order to ensure the safe operation of energy storage power stations, it is necessary to study the explosive characteristics of prefabricated cabin lithium-ion battery energy storage power stations.

Due to the high cost and extremely high risk of explosion experiments in real energy storage scenarios [12,13], in order to maximize the restoration of the working environment of energy storage plants and to study the process and hazards of gas explosions in prefabricated chambers. Use finite element analysis software to establish gas explosion models of single-layer prefabricated cabin energy storage power station and double-layer prefabricated cabin respectively, and select key parameters by changing the initial explosion conditions such as the location of the initiation point, and key parameters (e.g., temperature, maximum pressure value, maximum pressure rise rate, etc.) were selected for sensitivity analysis of different detonation conditions to study the gas explosion characteristics of the single-layer energy storage prefabricated chamber.

The geometric size of the energy storage cabin of the single-layer prefabricated energy storage cabin is 12 m×2.4 m×3 m, and the simulation area of a single energy storage cabin is 32 m×12 m×6 m. There are aisles inside the energy storage compartment, and large geometric bodies such as battery racks, battery module shells, and battery modules are symmetrically arranged on both sides of the aisle; each side of the battery rack has 7 layers and 16 columns, and the cell size is 0.8 m×0.6 m×0.3 m; The size of the battery module shell is 0.7 m×0.5 m×0.25 m, and there are multiple vent holes on the shell to facilitate the heat dissipation of the battery module. The battery module size is 0.6 m×0.4 m×0.24 m. The energy storage cabin is equipped with 4 pressure relief plates, two of which are located at the doors at both ends of the cabin body, and the opening pressure is set to 20kPa; The other two pressure relief plates are located in the upper middle of both sides of the cabin body, with a height of 2.4m, and the opening pressure Set to 3kPa.

In order to make a detailed analysis of the change process of each key parameter, an array of monitoring points with the same horizontal arrangement is set up at three levels in the energy storage cabin, and the positions inside the cabin and outside the pressure relief plate are mainly studied. The horizontal arrangement of the monitoring points is shown in figure 1. Each point has monitoring points at three heights of 0.7m, 1.7m and 2.7m.
Figure 1. (a) Energy storage warehouse (b) 3D view of the horizontal arrangement of monitoring points (c) Top view of the horizontal arrangement of monitoring points.

The rest of this article is arranged as follows. The second part compares and analyzes the explosion effects of different initiation points. The third part summarizes the full text and puts forward conclusions.

2. Different Initiation Points

2.1. Experimental Setup
The location of the detonation point determines the starting point of propagation of the subsequent explosion overpressure wave and flame wave, which directly affects the direction of the explosion
impact and the propagation process. The surrounding environment is relatively complex detonation point, the compression wave in the superposition process will be more disorderly, and its overpressure in the subsequent development process by the environmental hindrance will appear more complex changes, more intense turbulence will also increase the rate of gas combustion, so that the explosion effect is more significant. Therefore, in this section, the coordinates of the central initiation point in a typical explosion scene are translated in the X-axis, Y-axis and Z-axis directions, and the explosion effects of different initiation points are compared and analyzed. According to the geometric structure of the energy storage cabin and the setting of the pressure relief plate, the energy storage cabin is divided into a symmetrical double-sided door prefabricated cabin and an asymmetrical single-sided door prefabricated cabin for separate research.

First, the coordinates of the central detonation point in a typical explosion scene are translated in different directions, and the peak overpressure in and outside the cabin, the peak value of the pressure rise rate in and outside the cabin, and the temperature are selected as the monitoring indicators. The explosion effect is summarized in table 1.

2.2. Experimental Results
The difference in the explosion effect of different initiation points is reflected in the following aspects: the initiation point No. 1 is the central initiation point in a typical explosion scene, and the initiation point No. 2 and 3 are translated in the Z-axis direction based on the center point, and the peak overpressure in the cabin after translation were reduced by 27%, and the peak DPDT in the cabin of No. 2 detonation point also decreased by 25%, indicating that the lower detonation explosion overpressure on the cabin relatively small impact; and No. 3 higher detonation in the cabin DPDT peak increase of 42%, and the two pressure relief panels set above the bulkhead in the explosion process was the first to be washed away, the relatively complex airflow direction led to a more complex pressure wave superposition complex.

| Serial number | Initiation point | In the cabin | Outside the cabin | Peak temperature (K) |
|---------------|-----------------|--------------|-------------------|----------------------|
|               | Pmax (kPa)      | DPDTmax (kPa/s) | Pmax (kPa)      | DPDTmax (kPa/s)      |                        |
| 1             | (6, 1.2, 1.7)   | 28.96        | 3929             | 15.27                | 10067                 | 2112                  |
| 2             | (6, 1.2, 0.7)   | 21.07        | 2946             | 9.73                 | 30226                 | 2095                  |
| 3             | (6, 1.2, 2.7)   | 21.07        | 5715             | 16.48                | 10405                 | 2111                  |
| 4             | (3.5, 1.2, 1.7) | 20.99        | 2894             | 10.3                 | 10179                 | 2089                  |
| 5             | (1, 1.2, 1.7)   | 29.6         | 1579             | 13                   | 7376                  | 2076                  |
| 6             | (1, 0.3, 1.7)   | 31.89        | 1754             | 12.2                 | 8805                  | 2103                  |

Relative to the center detonation of No. 1, No. 4 and No. 5 are the detonation points that move in the X-axis direction. Comparing the two cases 1 and 4, it can be seen that when the detonation point approaches the door end, the external pressure peak, internal pressure peak, and DPDT peak all decrease, and only the external pressure rise rate peak remains close. The explosion results of the No. 5 case showed that when the detonation point moved further in the negative direction of the X-axis to close to the door, the pressure peak points inside and outside the cabin were close to the detonation point, and the value did not drop significantly; The DPDT peaks inside and outside the cabin have a downward trend, indicating that the obstruction and loss encountered in the process of overpressure propagation outside the cabin are more obvious. In the case of No. 5 and No. 6, the detonation point moves in the Y-axis direction, but due to the limitation of the cabin structure, the detonation point translation is small, and the pressure peak and the pressure rise rate peak change are not obvious.
The commonality of the explosion effects at different initiation points is that the range of the peak overpressure in the cabin is 1-1.6 times the opening pressure of the door; the peak values of the overpressure outside the cabin are all lower than those in the cabin, indicating that the pressure wave has a significant loss in the process of propagating to the outside of the cabin; The DPDT peaks outside the cabin at different initiation points are all higher than those in the cabin, also because the outside of the cabin has not experienced the early development stage of the explosion. In addition, the temperature peaks at different initiation points are all around 2100K, indicating that the change of the initiation point has little effect on the temperature peaks.

Then select the special initiation point to analyze the explosion process at the special location in the cabin. In the symmetrical double-side door prefabricated cabin, according to the position of the detonation point relative to the pressure relief hole at the door with the largest pressure relief area, the detonation types can be divided into central detonation and door end detonation. The pressure curve of each pressure relief plate during the explosion is shown in figure 2.

![Pressure curve of each pressure relief plate during the explosion.](image)

**Figure 2.** Pressure curve of each pressure relief plate during the explosion.

Here, select the detonation point with coordinates (1, 1.2, 1.7), select the combustion rate as the monitoring indicator, and analyze the change process of the combustion wave when the door is detonated. Due to the symmetry of the cabin in the Y-axis direction, select the area showing Y>0.9m in order to observe the changes of the combustion wave in the cabin, as shown in figure 3.
Figure 3. Variation Process of Initiation and Combustion Rate at the Door End in Symmetrical Structure.

In figure 3(a), it can be seen that the flame wave is still spreading around in a spherical shape at first. The high heat generated by the combustion is transferred to the nearby unburned area, and the surrounding temperature is increased to cause the unburned combustible gas to undergo a chemical reaction, so as to achieve energy transfer and flame spread. It can be seen in figure 3(b) that 0.39s after initiation, the flame wave develops to the unburned area in the form of a curved surface, and the burning rate of the middle layer of the flame wave is relatively large, and the peak value can reach 10kg/(m3*s). The side of the flame wave close to the detonation point belongs to the burned zone. As the concentration of combustible gas in this area is continuously reduced, the burning rate is at a lower level; The side of the flame wave far away from the detonation point belongs to the unburned zone, and it is in a heating and pre-ignition state due to the heat transferred from the flame wave middle layer. Figure 3(c) can be seen in 0.4s after the detonation, closer to the detonation point of the left hatch has been flushed open, the flame wave propagated to the outside of the cabin, but because of the limited content of the left side of the gas, so the rate of combustion outside the cabin is always below 5kg / (m3 * s), and the propagation distance is limited; the flame wave in the cabin continues to develop to the unburned area on the right side. Because the 3#4# pressure relief plate on the side of the cabin body is flushed, the explosion venting airflow in the Y-axis direction causes the flame wave to propagate slightly to the right side of the X-axis slightly decreased; in addition, it is noted that the battery module shell is attached to the flame, and the many vent holes on it increase the disturbance to the flow direction of the combustible gas in the module box. It can be seen in figure 3(d) that 0.44s after the detonation, although there is still flame outside the left cabin door, with the consumption of combustible gas, the burning rate value decreases significantly, and the farthest propagation distance of the flame outside the left cabin is 3m. It can be seen in figure 3(e) that 0.48s after the detonation, the flame range outside the left side door is further reduced; after the flame wave in the cabin has passed the 3#4# pressure relief hole position, the propagation speed to the right end is increased, and the flame wave The shape is close to a laminar flame, spreading in the channel with a front shape. Fig.
3(f) and (g) show the picture 0.49s after the detonation. The flame wave reaches the right side door, and still keeps the front shape and propagates to the open environment outside the cabin; afterwards, the cabin door was flushed open, and the gas flow became more irregular, causing the shape of the flame wave to be unable to be maintained; in addition, figure 3(g) can be seen on the right side of the flame wave propagation distance of 6m outside the hatch, far beyond the left side of the hatch outside the 3m, reflecting the role of the detonation point on the effect of the explosion. When the flame wave propagates to the right side in the prefabricated cabin channel, it has a longer acceleration time and a more sufficient combustion effect, so the flame wave on the right side travels farther; in addition, the amount of combustible gas that was flushed out with the shock wave outside the right-hand cabin door was more, which also caused the burning phenomenon outside the right-hand cabin to be more intense. Figure 3(h) shows the picture 0.61s after the detonation, when the explosion has basically ended.

3. Conclusion
In this paper, the explosion characteristics and protection strategies of single-layer energy storage compartments are studied by sensitivity analysis of the locations of different initiation points. Through the comparative study of different initiation points, it is found that the overpressure peak at different initiation points varies from 1 to 1.6 times the opening pressure of the cabin door. The overpressure peak of the detonation at the near end of the door is lower than that at the far end, which reflects the effect of releasing the explosion energy to the outside of the cabin as soon as possible after the detonation.

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