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Using Fire Dynamics Simulator (FDS) to Explore the Fire Hazard Zone of 40-Foot Energy Storage System

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Abstract: - In recent years, due to issues such as air pollution and global warming, green energy such as wind power and photovoltaics has developed rapidly. However, whether it is wind power generation or solar photovoltaic, it is necessary to use energy storage system to regulate the power system to maintain the balance and stability of power supply. However, there have been many fire accidents of energy storage systems in the world, causing difficulties in fire rescue. This study takes current a 40-foot energy storage system as a case in Taiwan, uses the Fire Dynamics Simulator(FDS) to discuss the situation of the fire in this case, the situation of the fire spread, and the fire extinguishing efficiency of the water sprinkler system. Based on the results of FDS computer simulation, an evaluation method for the fire hazard zone of fire rescue is established, and a mechanism for fire prevention, emergency response and fire rescue of energy storage system is established.

Keywords: Energy Storage Systems, Fire Dynamics Simulator(FDS), Fire spread, Fire hazard zone, Water mist.

I. INTRODUCTION

In response to the global trend towards green energy and smart grids, governments worldwide have been actively promoting the development of balanced grids and supporting the growth of energy storage systems, hereinafter referred to as "energy storage systems". In line with the international environmental protection policies, the number of energy storage systems installed in Taiwan is also rapidly increasing. Due to factors such as energy density, technological maturity, and cost considerations, lithium-ion batteries are currently the mainstream form of energy storage system used worldwide [1]. Therefore, with the development of green energy, technologies for storing intermittent energy sources are increasingly being emphasized [2]-[4]. When the proportion of green energy in the general power system reaches a certain level, adjustable energy storage systems are needed to maintain supply-demand balance [5]. Currently, there are various forms of storing electrical energy, including mechanical energy, thermal energy, electrochemical energy, and grid energy storage [6]. However, in recent years, there have been multiple incidents of fires involving energy storage systems internationally and in Taiwan.

For example, between 2017 and 2022, there were 28 incidents of energy storage system fires in South Korea [7], and these fires not only affected the power supply system but also posed challenges for firefighting and rescue efforts.

Battery Energy Storage System (BESS) is a technological device that utilizes batteries to store electrical energy in electrochemical form. It can be used to store energy during low grid loads and output energy during high grid loads, for peak shaving and load shifting, thus mitigating grid fluctuations. With current human technology, lithium-ion batteries (Li-Ion Battery) have advantages such as environmental adaptability, rapid response, high power, high energy density, technological maturity, and rapidly declining costs. They currently account for over 90% of the global cumulative installed capacity of electrochemical energy storage, and are also the mainstream technology for large-scale energy storage systems in Taiwan. In just the United States, over the past decade, the usage of energy storage systems (ESS) composed of lithium-ion batteries, including those based on Iron Phosphate (LFP) or Nickel Manganese Cobalt Oxide (NMC), has grown from 1 MW to nearly 700 MW [8].

According to the LI-ION Tamer report dated June 14, 2019 [9], the main reasons for the 23 lithium-ion battery energy storage system fires that occurred in South Korea from August 2017 are as follows: 1. Insufficient battery protection systems against electric shock; 2. Inadequate management of operating environment; 3. Faulty installations; 4. ESS System Integration. From the aforementioned, it is evident that due to the unique nature of fires involving energy storage systems, adjustments should be made to firefighting and rescue strategies. Therefore, this study aims to use Fig. 1 as a case study to establish clear fire alert zones for energy storage systems,

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serving as a reference basis for subsequent emergency response and firefighting strategies.

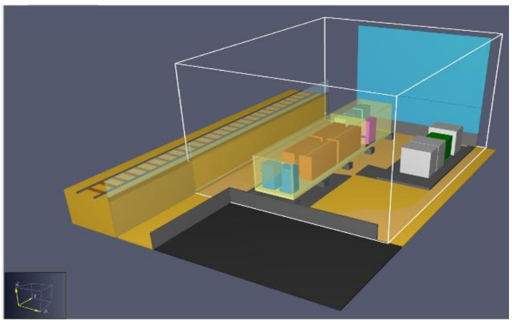


Fig. 1. The 40-foot Energy Storage Sation in Pingtung, Taiwan.

II. FIRE CASE STUDY DESCRIPTION

A. Fire Incident at the Solar Photovoltaic Power Generation Equipment in Qigu District, Tainan, Taiwan

On September 7, 2020, in the Qigu District of Tainan, Taiwan, a fire broke out at a solar photovoltaic equipment site. Flames were observed on the west side of one of the containers, with dense black smoke emanating from within. Upon inquiry, it was revealed that the container housed solar photovoltaic equipment such as transformers and inverters, with a burning area of approximately 5 square meters. The on-site contractors assisted in cutting off the power supply. The firefighting operation was carried out by the Qigu Fire Department, deploying an attack vehicle (No. 11) equipped with a 2.5-inch water hose and bifurcating it into two lines with 1.5-inch water hoses for direct firefighting. Another vehicle (No. 15) served as a water source, as there were no ground hydrants on site. Water was relayed from vehicle No. 15 to vehicle No. 11 for firefighting purposes. The firefighting operation at the scene is depicted in Fig. 2.

Fig. 2. Fire Incident at the Solar Photovoltaic Equipment Site in Tainan, Taiwan.

B. Fire Accident at the Energy Storage Station in Taichung, Taiwan [10]

On July 5, 2023, a fire accident occurred at a container energy storage station located along the roadside in Longjing District, Taichung City, Taiwan. Upon investigation, it was found that the point of origin was within the storage unit. Three 20-foot containers were placed on-site to store green energy storage batteries. Due to the outdoor temperature reaching approximately 35 degrees Celsius, the manufacturer had only implemented explosion-proof protection measures without installing sunshade and heat insulation equipment, resulting in extremely high temperatures. The burning area was approximately 30 square meters, as shown in Fig. 3. Since the containers housed lithium iron phosphate batteries, there was a risk of electric shock during the firefighting process, and hastily opening the container doors could lead to instantaneous ignition or explosion. After notifying the manufacturer to cut off the power supply and spraying water to cool down the area, a fully equipped firefighter opened the container door and extinguished the fire with foam inside the container. Continuous cooling of the batteries with water was carried out, fortunately resulting in no casualties.

Fig. 3. Photograph of the Scene of the Fire Accident at the Energy Storage Station in Taichung, Taiwan.

C. Fire Incident at the Energy Storage Cabinet in Orchid Island Power Plant, Taiwan [11]

The incident occurred on December 28, 2023, as depicted in Fig. 4. During grid integration testing of the "Power Storage and MR Hybrid Reality" system newly installed at the Orchid Island Power Plant, a fire broke out suspected to be caused by thermal runaway resulting from a short circuit in the energy storage system battery cells. The fire spread to other batteries and ignited due to the accumulation of a large amount of flammable gas. During the process, the door of the energy storage cabinet popped open due to gas expansion. The fire was quickly brought under control by the plant area and testing personnel. To prevent the fire from spreading further, the Orchid Island Fire Brigade was requested to maintain perimeter security until the situation was resolved.

Fig. 4. Photograph of the Fire Scene at the Energy Storage Cabinet in Orchid Island Power Plant.

III. COMPUTER SIMULATION ANALYSIS

This study utilizes the Fire Dynamic Simulator (FDS) computer simulation program for conducting fire scenario simulations. Developed by the National Institute of Standards and Technology (NIST) in the United States [12], the program was first publicly released in February 2000 with ongoing improvements. FDS is a Computational Fluid Dynamics (CFD) software that employs a field model to simulate various fire scenes [13]. Currently, the program is internationally recognized and widely used [14]. In this study, the latest version of FDS 6.80, published in April 2023, is employed to construct the numerical model for computer simulation of this case. The input parameters for the FDS computer simulation program in this research case are based on experimental data from Chapter 3 and relevant experimental data from NIST. By reconstructing this fire scenario and assessing the variations in fire hazard factors, the study aims to determine the causes of firefighter casualties.

A. Optimization of gid analysis

Due to the large scale of the fire simulation space in this case, setting the grid size too large during computer simulation calculations may result in insufficient accuracy of the entire fire scene simulation. Conversely, setting the grid size too small may consume a significant amount of computer memory capacity, rendering the simulation infeasible. Therefore, this study conducts grid optimization analysis using Equation (1) [12] as follows:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{q \cdot A}{\rho_0 \cdot \frac{T_0}{T_\infty} \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{q \cdot A}{\rho_0 \cdot T_0 \cdot C_P \cdot \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

In which q represents the Heat Release Rate Per Unit Area (HRRPUA) of the building. This study adopts a value of 14,061 kW/m based on relevant literature [15].The air density ρ_0 is 1.2 kg/m^3 and the specific heat Cp is 1.0。The initial temperature T_0 =273+27=300 K。

The aforementioned data is substituted into Equation (1) as follows:

$$D^* = \left(\frac{q \cdot A}{\rho_\infty \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{14061 \cdot 1.0}{1.2 \cdot 300 \cdot 1.0 \cdot \sqrt{9.81}}\right)^{\frac{2}{5}} = 2.7$$

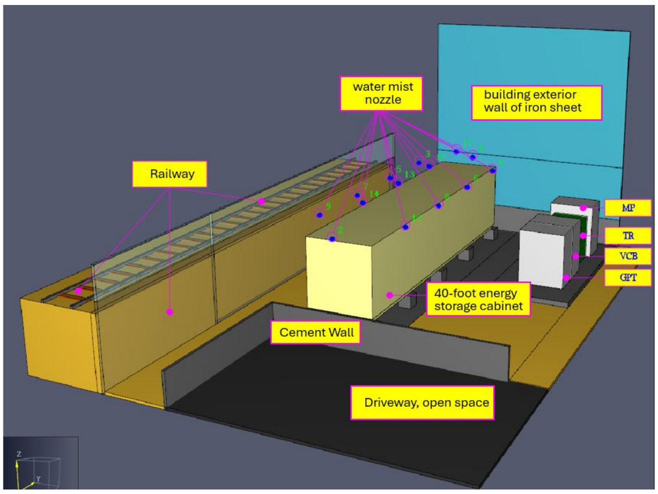
After repeated simulations and testing, this study proposes to use a grid size of 0.2 m. Therefore, the calculation formula (2) is as follows:

$$\frac{D^*}{dx} = \frac{2.74}{0.2} = 13.72 \quad (2)$$

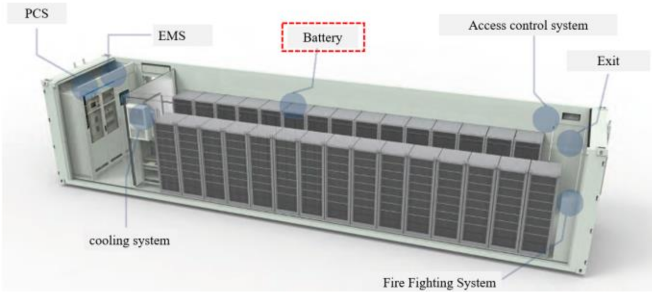
According to the literature research results of grid optimization analysis [12], the aforementioned ratio of 13.72 falls within the range of 4 to 16. Therefore, this study adopts a grid size of 0.2 m × 0.2 m × 0.2 m, which should be reasonably acceptable.

B. Data model

Based on Fig. 1, this study constructs an FDS computer model using the relationship diagram between the 40-foot energy storage container and adjacent areas. Referring to section 2.3, areas with high severity and high risk are selected as ignition points, with the energy storage cabinet at the station identified as the high-risk ignition point. The numerical model for fire simulation is constructed with simulation dimensions of X-axis 12 m, Y-axis 15 m, and Z-axis 10.0 m, as illustrated in Fig. 5. According to section 3.1 on grid size analysis, a grid size of 0.2 m × 0.2 m × 0.2 m is adopted in this case. The number of grid points in the fire simulation area is 60 × 75 × 50, with a total of 225,000 grid points in the simulation space.



(a) FDS Simulation Configuration Diagram



(b) The 40-foot Energy Storage Container at the Site

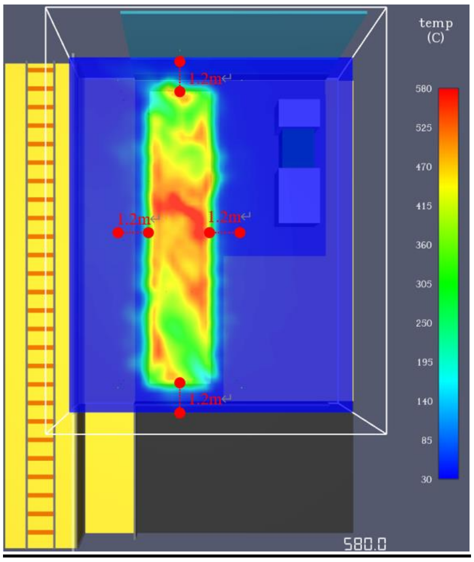
Fig. 5. Diagram depicting the relationship between the 40-foot energy storage container and adjacent areas.

IV. ANALYSIS OF COMPUTER SIMULATION RESULTS

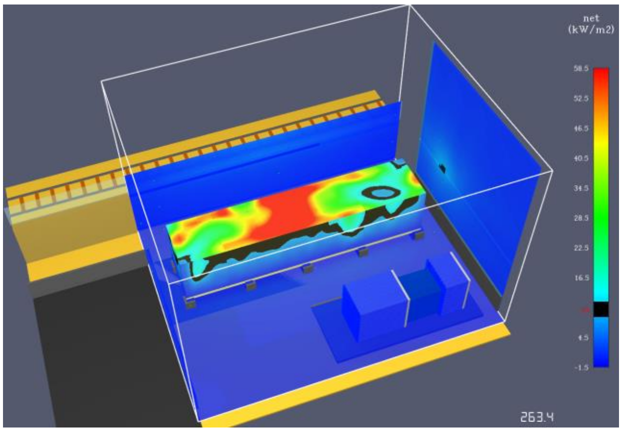
This study utilizes the Fire Dynamic Simulator (FDS) computer simulation to simulate two scenarios: CASE 1, which represents a situation without firefighting protective equipment, and CASE 2, which represents a scenario with a water sprinkler fire suppression system installed. By comparing the fire heat radiation effects in CASE 1 and CASE 2 on surrounding equipment, the study aims to assess the safety hazard range of the fire.

A. CASE 1 (Fire inside ESS without Water Sprinkler)

According to Fig. 5, the highest temperature above the roof of the energy storage container can reach 530°C, and it remains within the range of approximately 230~380°C. The temperature between the container and the adjacent wall of the neighboring factory can reach around 180~230°C. Additionally, on the northwest side of the container, approximately 1.2 meters away from the neighboring factory's metal wall, the highest temperature can reach 65°C and remains between 45~65°C. The factory wall will remain heated for a long time at high temperatures, requiring personnel wearing firefighting gear to approach only with the protection of water sprinkler. The attack direction should be from the side and avoiding the opening. According to Fig. 6, the neighboring factory wall on the northwest side is expected to experience radiative heat flux exceeding 22.5 kW/m^2 for approximately 263.4 s, posing a risk of fire radiation spreading.



(a) Temperature Variation Chart

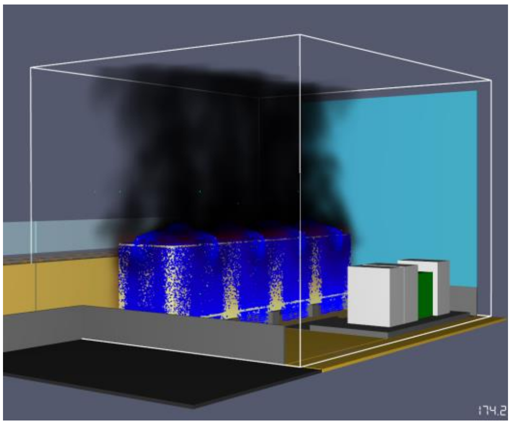


(b) Heat Radiation Variation Chart

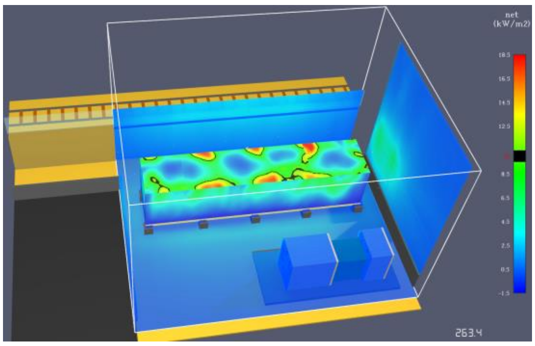
Fig. 6. Simulation Results for CASE 1.

B. CASE 2 (Fire inside ESS with Water Sprinkler)

This study utilized an operating pressure of 3.50 kg/cm² (3.43 bar) for the on-site water sprinkler nozzles, with a K-Factor of 79.1 lpm/bar$^{1/2}$. The water sprinkler flow rate was calculated to be 145.53 L/min (following a rigorous design). The water sprinkler particle size was set at 1,000 µm. According to the FDS computer simulation, after the activation of the water sprinkler fire suppression system, the heat radiation near the adjacent walls decreased to below 6.5 kW/m^2 within approximately 263.4 s. There should be no risk of fire propagation. As shown in Fig. 7, comparing CASE 2 with CASE 1 reveals a significant effect of the water sprinkler system activation in reducing the temperature of surrounding equipment and blocking the propagation of heat radiation.



(a) Activation of Water Sprinkler System



(b) Heat Radiation Variation Chart

Fig. 7. Simulation Results for CASE 2.

V. CONCLUSION AND RECOMMENDATIONS

This study utilized a 40-foot energy storage container in Taiwan to construct an FDS model, setting the scenario of combustion occurring in the lithium-ion batteries inside the storage system to evaluate the conditions in the surrounding environment. This was done to assess the fire alert area. From the results, it is evident that without protection, and with the container door closed due to gas expansion, the heat radiation at a distance of 1.2 meters on the northwest side of the adjacent factory wall exceeds 22.5 kW/m^2. With water sprinkler protection, the surrounding area of the storage container can effectively cool down, reducing the surrounding heat radiation to 6.5 kW/m^2. According to NFPA 855 (4.6.2) recommendations [16], the minimum distance between each set of storage systems should be 3 ft (0.914 m). Additionally, according to the Taiwanese Ministry of Economic Affairs' "Technical Regulations for Verification of Outdoor Battery Energy Storage Systems," the spacing between battery cabinets in general energy storage systems should be at least 1.5 meters to allow for the passage of personnel.

According to research data, human skin can be harmed when exposed to temperatures exceeding 44°C and heat radiation levels of 1.7 kW/m^2. Depending on the degree of heating, this can result in minor or severe burns, or even death. When the heat radiation level reaches 2.0 kW/m^2, the safe exposure time for an average person is approximately 22.33 s. At 3.0 kW/m^2, exposure for more than 10 s can cause skin damage. Exceeding 7.0 kW/m^2, burns can occur in just 2 s of exposure. Considering the above, in the case of this research scenario with a spacing of approximately 1.2 meters between battery cabinets, there should be no concern about fire spreading. However, regarding firefighting personnel rescue, if rescue personnel are not wearing firefighting protective clothing and there is no water sprinkler protection, they may sustain injuries when located 1.2 meters away from the fire source. Therefore, it is recommended for firefighting personnel to wear appropriate protective gear and maintain a safe distance of at least 5 meters from the fire source.

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