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Research Article

Numerical Simulation of Chemical Storage Tank Area Leakage and Explosion Accident Based on FLACS

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The large amount of oil storage tank possesses significant risks of leakage, and once leakage occurs, the combustible gas is prone to fire and explosion accidents. When the combustible gas cloud is exposed to the ignition source, there are possibilities of triggering the domino effect with more serious consequences. As one important kind of protective layers, the combustible gas detectors continuously monitor the leakage of combustible gas, guaranteeing the safety performance of the site. Using the computational fluid dynamics software FLACS as a tool, the impact of the consequences of the raw material leakage with a vapor cloud explosion accident in a large chemical fiber manufacturer's storage tank area is studied, and the risk of domino effect in the tank area during the course of the accident is predicted. The study shows that FLACS can be applied to the simulation study of gas diffusion explosion phenomenon in complex operation and storage areas, with the great capability of the explosion risk quantitative assessment and the reliable prediction to the risk of domino effects.

1. Introduction

As gasoline is flammable, explosive, and toxic, once it leaks, it may cause waste of resources or fire, explosion, poisoning, and other accidents and even escalate to the domino effect with more serious consequences [1, 2]. Combustible gas detectors as an important layer of protection, its automatic alarm function can quickly determine the location of the leak, prompting staff to take a series of measures to prevent accidents or prevent the escalation of accidents. However, the current setup of combustible gas detectors is generally arranged according to the relevant standard regulations or working experience, and the setup method is too subjective, resulting in poor detection effect. The arrangement of combustible gas detectors should conform to the law of gas diffusion, but the external environmental conditions such as wind direction, wind speed, and temperature, as well as the obstruction of equipment in the tank area make the process of gas leak diffusion more complicated. The development of information technology [3–7], computational fluid dynamics (CFD) [8–12], and their integration has brought new opportunities to numerical simulation of chemical storage tank area leakage and expansion accident. Therefore, the method based on computational fluid dynamics to simulate the consequences of gas leak diffusion to determine the location of detectors is gradually being used. CFD-based methods for determining the location of detectors are becoming widely used.

2. Analytical Principles and Methods

2.1. Analysis Principle. FLACS is a three-dimensional consequence simulation software based on fluid dynamics (CFD) calculation technology developed and launched by the Norwegian company Gexcon, which is widely used in the simulation of ventilation, leakage, diffusion, fire and explosion consequences in complex process areas. Nowadays, FLACS software [13, 14] has been verified by many experiments and has shown obvious advantages in oil and gas and process industry applications. FLACS is the only CFD software approved for all LING vapor dispersion scenarios required in the siting of LNG facilities, as described in 49CFR193.2059 of the U.S. Federal regulations. In 2010, FLACS software is used for the first time to study the effect of obstacles and complex geometry on air and vapor flow after flashover of a high-pressure jet and to determine the hazard distance of gas cloud diffusion in a flashover accident. Researchers studied the explosion hazard range of gas clouds from leaking LNG tanks by combining theoretical models, numerical simulations, and experiments and found that the results of gas cloud diffusion in three ways were basically the same when the leakage volume was small [15–17]. In 2019, Wang analyzed the effects of wind direction, wind speed, and weir height on the consequences of LNG gas cloud diffusion by using relative deviation rate and found that within 300 s of leakage, weir height has the greatest effect on the diffusion of gas cloud leakage. In 2019, Qin et al. used CFD software to simulate and calculate the dispersion characteristics of gas clouds of storage tanks under different obstacle conditions, taking the actual storage tanks of receiving stations as the prototype [18]. The relevant studies by these scholars basically confirmed the image laws of wind direction and wind speed and other indicators when using FLACS for the analysis of LNG storage terminal leakage. However, there is still a gap in the study of leak location and obstacles that can also affect the diffusion of LNG storage terminal leaks. Therefore, the research in this paper is based on the research methods of related scholars and complements the two indicators of leakage location and obstacle of LNG storage terminal leakage dispersion.

2.2. Analysis Method. First, this paper will be guided by the principles of fluid dynamics calculation, and FLACS software will be used to solve the Navier-Stokes control equations in a three-dimensional Cartesian coordinate system and perform the task of turbulence processing with the standard k—ε turbulence model to obtain the flow field changes and chemical reaction processes in a specific region [19]. Second, the CASD preprocessing software is opened by running FLACS RunManager and the geometric model is constructed in Geometry⟶Database, where the creation of Materials (model colors), Objects (geometric parts), and Geometry (geometric components) is addressed. Finally, the model is validated, and the gas diffusion is visualized with the help of FLACS′ postprocessor Flowvis, which performs 2D and 3D graphical output of various variables and automates the video generation and data analysis. With the help of Flowvis, a postprocessor of FLACS, it is possible to visualize the gas diffusion, perform 2D and 3D graphic output operations on various variables, and complete the automated video generation, which is of positive significance for the presentation and evaluation of the results [20].

3. Numerical Simulation of Chemical Storage Tank Area Leakage Explosion Accident Based on FLACS

3.1. Theoretical Model. The FLACS explosion model has been validated by full-scale tests and is widely used in the field of natural gas leak explosion [21–23]. FLACS couples turbulence and chemical reactions and establishes the mass, momentum, energy, and component conservation equations describing the fluid characteristics. The finite volume method with boundary conditions is used to solve for the values of variables such as overpressure, combustion products, flame velocity, and fuel consumption in the computational region as follows:

$$\frac{\partial}{\partial t}(\rho\varphi)+\frac{\partial}{\partial x_j}\left(\mu_j\rho\varphi\right)+\frac{\partial}{\partial x_j}\left(\Gamma_\varphi\frac{\partial\varphi}{\partial x_j}\right)=S_\varphi, \tag{1}$$

where φ is the generic solution variable (including mass, momentum, energy, and other variables), ρ is the gas density, t is time, and xj represents the j coordinate position in the direction, μj represents the velocity vector in the j direction, $\Gamma\varphi$ is the diffusion coefficient, and $S\varphi$ is the source term. The method takes into account the interaction and influence between the flame and obstacles such as equipment and pipes and can be directly calculated for the explosion shock wave. FLACS turbulence model is the standard k-ε model, which belongs to the two-equation model in the vortex viscosity model, and the transport equation for the turbulent kinetic energy k is as follows:

$$\begin{aligned}\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho k\mu_j\right)}{\partial x_j}&=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]\\&\quad+G_k+G_b-\rho\varepsilon-Y_m+S_k.\end{aligned} \tag{2}$$

The transport equation for the dissipation rate ε is as follows:

$$\begin{aligned}\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial\left(\rho\varepsilon\mu_j\right)}{\partial x_j}&=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]\\&\quad+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon.\end{aligned} \tag{3}$$

In the formula, μ is the laminar viscosity coefficient, and μt is the turbulent viscosity coefficient [13].

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}, \tag{4}$$

where Gk is the generation term of turbulent energy k caused by the mean velocity gradient; Gb is the generation term of turbulent energy k caused by buoyancy; Ym represents the contribution of pulsation expansion in compressible turbulence; σk is the Prandtl number corresponding to the turbulent energy k, taken as 1.0; $\sigma\varepsilon$ is the Prandtl number corresponding to the dissipation rate ε, taken as 1.3; Sk and Sε are the user-defined source terms; $C1\varepsilon$, $C2\varepsilon$, $C3\varepsilon$, and $C\mu$ are empirical constants, taken as 1.44, 1.92, 0.80, and 0.09, respectively.

3.2. Simulation Scenario Setting and Geometric Model. The raw material tank unit of a large chemical fiber production enterprise consists of four vertical vault tanks of the same size, the storage medium is naphtha, the tanks are made of low alloy rigid material, normal temperature and pressure storage, the top of the tank is an internal floating roof with nitrogen seal, and the internal floating disk adopts a secondary seal [24–26]. Single tank volume $V = 20,000\,m^3$, diameter $D = 38\,m$, tank height $H = 17\,m$. The east side of the tank area is equipped with substation room, foam station, sewage tank, and pumping unit. The distance between the tanks is 23 m, the distance between the tanks and the fire embankment (dike) is 9 m, the height of the fire embankment of the whole tank group is 1.8 m. In order to reduce the scope of influence caused by the leakage accident of the tanks in the fire protection, the dike is used to separate the tank group into two partitions, each partition contains two tanks, the height of the fire protection dike is 0.8 m, the design liquid level in the tank area is 1.5 m, and the effective volume of the fire protection of the tank group is $29\,107.31\,m^3$. The specific arrangement of the tank area is shown in Figure 1.

Using the Flash leak module of FLACS software, assume that the bottom of storage tank T-01A inlet and outlet pipeline leakage, leakage aperture of 100 mm, leakage rate of 243 kg/*s*, leakage time of 10 s, after the leakage of naphtha in the fire dike to form a liquid pool, set up an ignition source near the side of the corridor, naphtha liquids are volatile liquids, encountering the ignition source is easy to occur after the vapor cloud explosion [27, 28]. Naphtha belongs to the mixture, its main component is alkane C5–C7 components; in the volatile gas, light components dominate.

3.3. Simulation Parameters Setting and Mesh Selection. The boundary conditions are set to "WIND" and "NOZZLE" in X and Y directions, and "EULER" in Z direction. Monitoring points were set along the leak point + Z direction, and two groups of 14 monitoring points were set on the surface of the tank wall in the storage tank (T-01A)-(T-01D) near the leak area; one monitoring point was set every 25 m on the two sides of the intermediate corridor, and eight monitoring points were set in total; one monitoring point was set on each side of the substation, foam station, sump, and pump room near the storage tank. The monitoring parameters are pressure and temperature [29].

Assume that the atmospheric temperature is 20°C, do not consider the influence of wind direction, the entire simulation space for $200\,m \times 150\,m \times 50\,m$ rectangular, divided into $150\,m \times 150\,m \times 45\,m$ total 1012500 grid for calculation, as shown in Figure 2. FLACS software calculates the gas combustion and explosion motion processes in each cell which are then integrated over all cells. Finally, we get the explosion results for the entire simulation space [30].

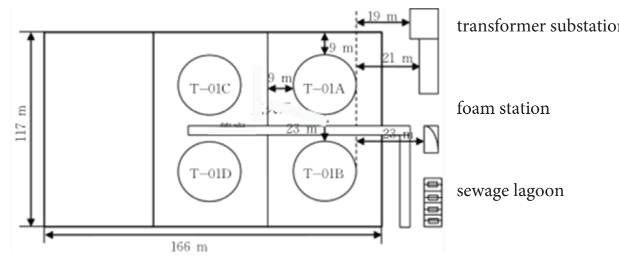

Figure 1: Tank area layout diagram.

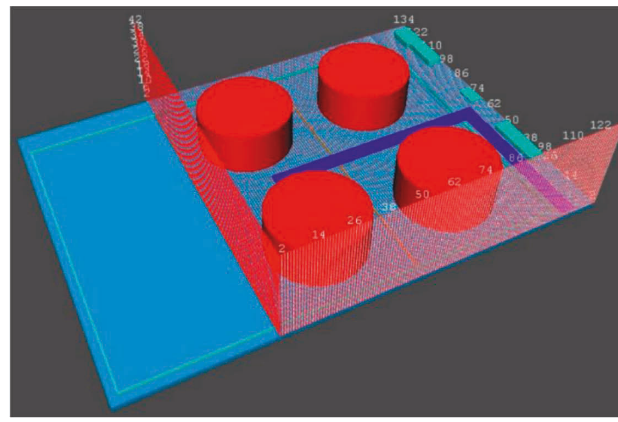

Figure 2: FLACS mesh model diagram.

4. Analysis of Simulation Results

4.1. Flame Spread. The XZ cross-sectional diagram is intercepted along the Y-axis to observe the flame propagation law of the leak source after the explosion of the vapor cloud at the ignition source [31, 32]. Figure 3 intercepts the XZ cross-sectional view of the center of the ignition source, the center of the pipe corridor, and the center of each storage tank, respectively. For the development of the flame throughout the leakage process, it can be found that the flame is first generated at the ignition source, and due to the rising effect of heat flow, a certain thickness of flame layer is formed at the upper part of the exploding gas cloud, shaped like a mushroom cloud, with a thin strip in the middle of the flame. The width of the flame can cover the intermediate corridor and leaking tanks, the ignition source as the center of the formation of the fireball diameter of about 20 m, the height of the flame is close to 40 m. The temperature of the outer edge of the flame is lower than the internal temperature, the temperature of the middle layer of the flame is lower than the temperature of the bottom and top, the maximum temperature of the flame can reach more than 2000°C. From the simulation results, the flames did not form direct contact with the three tanks outside the leaking tank.

4.2. Temperature Field Distribution. Figure 4 shows the temperature field distribution on the two sides of the middle corridor. It can be seen that the pipe wall temperature near the ignition source is high, away from the ignition source of the pipe wall temperature is close to the ambient temperature. The temperature of the pipe wall at the center of the

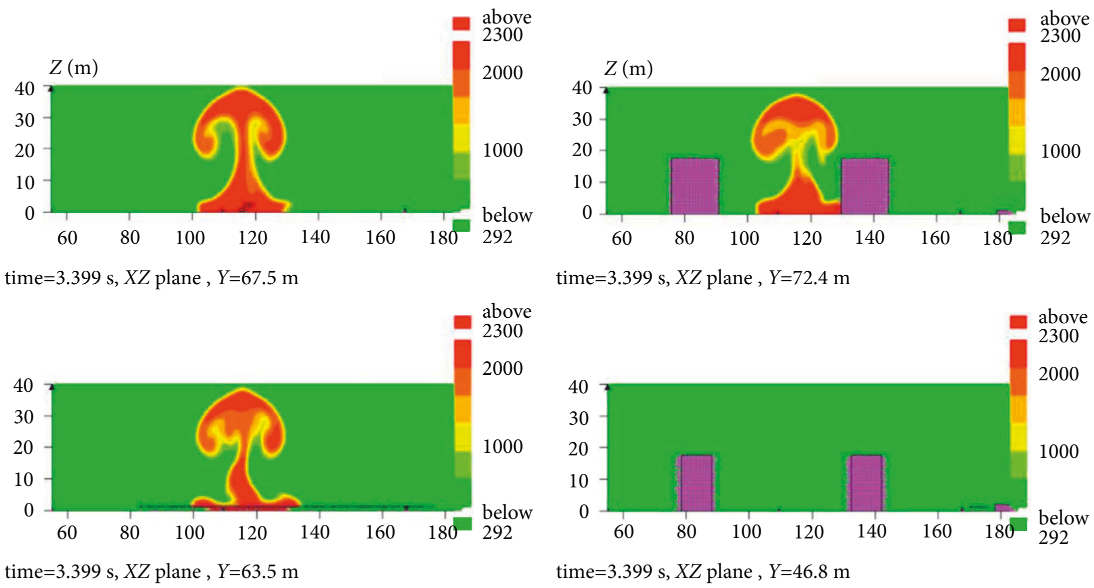

Figure 3: Flame development at different positions.

explosion flame is as high as 2,000°C, and the temperature of the pipe wall at the edge of the explosion flame is about 227°C, and the temperature decreases with the full reaction of the fuel [32–34]. Figure 5 shows the temperature distribution of the surface of the tank wall near the ignition source side of the leaking tank; it can be seen that the temperature of the tank wall did not immediately rise in the instant of the explosion but gradually increased with the development of the explosion flame, the highest temperature reached 4 s after the explosion, the highest temperature reached 2 000°C, and then with the end of the explosion process, the temperature of the tank wall dropped to about 200°C. From the simulation results, it can be seen that both the leaking storage tank and the intermediate corridor will be affected by the explosion and cause fire, two explosions, and other disaster accidents.

From the distribution of the temperature field on the tank wall surface throughout the leakage process (T-01B) -1000 (T-01D), the temperature of the tank wall is basically maintained at ambient temperature, and at the moment of the explosion due to fluctuations in airflow, the temperature only increased by less than 0.2°C, and then with the full reaction of the fuel, the temperature dropped to ambient temperature again. This is due to the short duration of the explosion, generally in the range of seconds, so the total amount of heat radiation received outside the explosion area is small; the temperature will basically remain near room temperature. However, the high temperature generated by the explosion will cause pool fires, flowing fires, and smoke, and in a long term, flame baking, smoke poisoning, and the impact of two explosions will produce damage and injury to the equipment and facilities outside the explosion area [35].

4.3. Pressure Field Distribution. From the simulation results, it can be found that the explosion generated the maximum overpressure of 2.9 kPa than the overpressure damage

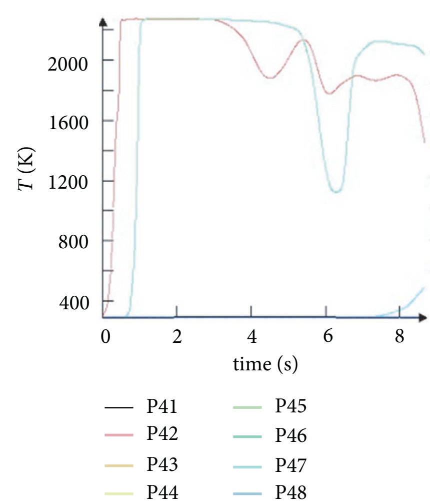

Figure 4: Temperature field distribution diagram on both sides of the middle pipe gallery.

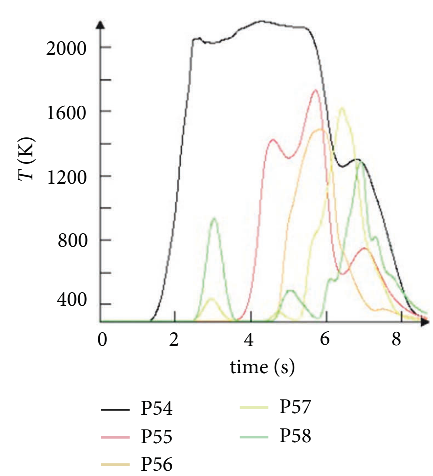

Figure 5: Temperature field distribution diagram on the tank wall on one side of the leakage storage tank near the fire source.

guidelines for minor damage overpressure value of 3.5 kPa is lower, so there will be no damage to neighboring buildings and structures.

5. Chemical Enterprise Storage Tank Area Leakage Explosion Emergency Management Problems and Optimization Measures

5.1. Analysis of the Problems of Emergency Management of Leaking and Exploding Storage Tank Areas in Chemical Enterprises (as Appropriate). Combining literature research, case law, and field visits to petrochemical enterprises, it is found that the following problems generally exist in the construction of emergency management in enterprises.

5.1.1. Low Importance of Emergency Management Deployment in the Top-Level Design of Enterprises. The development of enterprises depends on the top-level design to a great extent, especially for the construction of emergency management. Whether the person in charge of the enterprise can clearly understand the emergency culture, its connotation, and whether this emergency idea can be penetrated into the construction of the enterprise and implemented to the extent that all work is carried out around "safety first" and "preparedness," focusing on "It has a fatal impact on whether the enterprise can eliminate possible hazards in time and whether it can take active measures to implement rescue after the accident" [36].

5.1.2. Backward Early Warning Technology, Early Warning Processing Is Not in Place. Early warning as the most scientific and timely technical means of releasing danger signals is the "most important information" before the incident. If we can pay attention to and take active and effective preventive and control measures, we can completely avoid the occurrence of the incident. The advanced early warning technology, the normal operation of the early warning platform, the professionalism of the early warning information processing and integration staff, and many other factors will affect the attitude and treatment of the "signs." The data of typical major production safety accidents show that a large proportion of enterprises ignore the construction and use of safety monitoring systems and lack the awareness of intelligent early warning platforms to guide practical work.

5.1.3. Emergency Plans Are "Poorly Grounded". The emergency plan is a guiding document for enterprises to start emergency response and carry out emergency rescue operations in the face of emergencies, and its importance is self-evident. However, at present, most enterprises' emergency plans are entrusted to third-party safety intermediary service agencies for preparation. Looking at the plan, there are many problems in the preparation process, for example, whether the preparation process is based on a comprehensive assessment of the enterprise's hazardous and harmful factors, for the enterprise's special emergency plan, whether it is combined with the actual objective situation of the enterprise, is the more dangerous accident to unfold; for different response levels, whether the enterprise's rescue forces and rescue materials are true, and for different linkage collaboration departments, whether there is relevant communication.

5.1.4. Lack of Emergency Supplies Reserve. In other words, the proportion of emergency material reserve can also show the attention and importance of enterprises to the construction of emergency business to a certain extent. In addition, the emergency funds are not always executed as planed from time to time due to the lack of understanding to the safety and emergency management. This has led to the emergency supplies have been in the satisfaction of helmets, safety ropes, fire extinguishers, fire blankets, protective clothing and other simple items, while new, high technology emergency items are always "on the road." The construction of emergency teams is also limited to the internal strength of the enterprise [37].

5.1.5. Most of the Emergency Drills Are "Floating in the Form," With Poor Effect. According to the "Production Safety Accident Emergency Management Measures," enterprises are required to conduct emergency drills for the corresponding emergency rescue plans. This makes enterprises carry out emergency drills according to the actual situation. However, the following problems exist in the process of drills: first, weak emergency awareness and improper attitude of drills; second, multidepartmental and multiparticipant collaborative drills. A large part of the forces are not familiar with the content of the emergency plan, the purpose of the drill is not clear, for what each should do, how to cooperate and other issues are not clear. The drill becomes a walk-through: the main party of the emergency drill is on the problems and technical shortcomings. The main parties of emergency drills are still stuck on "paper" for problems, technical shortcomings, and poor linkage mechanism and fail to solve and revise the plan in a targeted way after the drills are over, which leave hidden dangers for "real combat."

5.1.6. Little Audience for Emergency Publicity. Emergency work concerns everyone, and many enterprises confine emergency propaganda and emergency work to emergency organizations, which is not a comprehensive understanding. In the face of a major disaster rescue, in addition to the emergency leadership group, command group, professional emergency teams, and so on, play a major role, each individual in the affected area has the necessary knowledge of certain emergency to carry out self-help and call for help; this contribution is immeasurable; in front of the accident, all people will be involved in the "community of fate." A small step by anyone can save the whole situation.

5.2. Emergency Management Measures for Chemical Enterprises to Prevent Leakage and Explosion in Storage Tank Areas. Combining the current problems in the construction of emergency management in enterprises, this paper puts forward the following suggestions.

5.2.1. Strengthen Emergency Management Training for Leaders at All Levels and Relevant Personnel. Each enterprise should carry out emergency management training in batches and at different levels. Combined with the emergency training audience, the training purpose should be clear and the training content targeted. For enterprise senior managers, the training would focus on topics related to the emergency management leadership and awareness to ensure the establishment of mature emergency management system. On the other hand, emergency rescue forces would improve their fire fighting skills, hazardous environment detection, decision-making, and response abilities by various training.

5.2.2. Pay Attention to the Preparation of Emergency Plans and the Effectiveness of the Implementation of Emergency Drills. The preparation and implementation of the emergency plan plays a key role in guiding the whole emergency rescue and disposal [38]. The preparation of the plan must comply with the objective facts on the basis of the full identification of enterprise risks and targeted emergency response. As a part of emergency plan preparation, the communication of the plan by brainstorming with expertise including the purpose, content, applicable scenarios, and cautions during rescue activities is also important to identify potential improvement for the plan. The plan can be improved and revised to ensure its operability.

5.2.3. Focus on Intelligent Construction to Provide Scientific Decision-Making. Strengthen the investment in intelligent construction of enterprises, introduce and integrate advanced technology as far as possible on the basis of budget, strengthen digital management, and provide a broader world for early warning and intelligent decision-making.

6. Conclusion

Compared with other numerical simulation software, FLACS software for complex explosion scenes and explosion propagation flame description more detailed, making the simulation results more realistic and accurate, and can be risk assessment results in the form of graphs and charts to express intuitively; in addition, the use of FLACS simulation technology for quantitative analysis of the domino effect in the process of accident expansion can effectively improve the accident near-field area. In addition, the quantitative analysis of the domino effect in the accident expansion process by using FLACS simulation technology can effectively improve the efficiency and accuracy of risk assessment of key equipment units in the near-field area.

Data Availability

The dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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