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Numerical Simulation Study on Oil and Gas Leakage and Diffusion under the Floating Roof Safety Landing Protection System in Large External Floating Roof Storage Tanks

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Abstract: Dangerous explosion accidents caused by oil and gas leakage accidents in storage tanks occur frequently. Research on the diffusion laws of oil and gas leakage in large external floating roof tanks is of guiding significance for the production safety of oil and gas leakage monitoring system in the oil storage tank area. Research on oil and gas leakage in oil storage tanks at home and abroad is mostly about oil and gas leakage diffusion laws in two cases: failure leakage of storage tank floating disk seal ring and leakage of tank top aperture. For large external floating roof oil storage tanks proposed by literature [1] There is no relevant research on the oil and gas leakage and diffusion laws of floating roof bottom protection systems in dangerous working conditions. Therefore, using this as the research object, FLUENT software simulation method is used to simulate oil and gas leakage accidents at its maximum oil collection speed. experiment. As a result, the oil and gas concentration distribution in the tank is affected by the flow field and is concentrated on the left side of the tank, and the concentration near the leakage port B is much higher than A. During the 450s of the leakage accident, the oil and gas concentration in the tank had reached 50% of the lower explosion limit. The research results have practical significance and theoretical value for the prevention and control of fire explosion risks of external floating roof tanks equipped with this safety protection bottoming system.

Keywords: External floating roof oil storage tank; floating roof bottom protection system; oil and gas leakage and diffusion; numerical simulation.

1. Introduction

Oil is an important national resource. my country has built 9 strategic oil reserve bases with a total storage capacity of 37.73 million cubic meters and a reserve day of 36 days, but there is still a gap compared with France (90 days), the United States and Japan (150 days).The National Petroleum Reserve Medium- and Long-term Plan is the goal of a hundred-day reserve days. Large oil storage tanks have become a development trend due to their investment savings, materials and small footprint. Common types of oil storage tanks include fixed top tanks, outer floating top tanks and inner floating top tanks. Among them, the outer floating top tanks have become the first choice for large and medium-sized oil storage tanks because the floating plate rises and falls with the liquid level and reduces oil and gas dissipation.

External floating roof oil tanks are widely used in liquid storage such as petroleum and chemicals. The floating roof design can reduce volatile evaporation and greenhouse gas emissions. However, the floating roof bottom operation leads to a decrease in volume utilization, which poses safety risks. After the floating roof falls to the bottom, the pillars support the floating roof, and the space below forms a dead volume, limiting the oil discharge, reducing the operating volume and economic benefits.In addition, increasing the size of the oil tank requires dismantling and reconstruction, which is costly and requires research on wind resistance and explosion resistance. Therefore, renovating existing oil storage tanks and studying safety protection technology for floating roof bottom operation is an important way to improve oil tank utilization and safety. The State Administration for Work Safety clearly stipulates that floating roofs and bottoms are strictly prohibited, further highlighting the urgency of technological improvement. Tao Jing[1] proposed a safety protection system for floating plate bottom. By renovating and designing the floating roof structure, the nitrogen injection inertification technology in the oil generation stage and the oil-gas mixture recovery technology in the oil collection stage are used to ensure the safe operation of the floating plate bottom, and ultimately improve the utilization rate of the oil tank by 10%.

Zhao Chenlu et al. [2,3] used FLUENT software to simulate the diffusion of oil and gas leakage in floating roof tanks. They found that the wind speed and high diameter ratio affect the distribution of wind pressure above the floating disk and the movement trajectory of the air flow, but did not study the oil and gas concentration distribution on the surface of the tank. Wen Jianjun et al. [4] simulated the diffusion of oil and gas in the inner floating roof tank and found that leakage time and wind speed affected the change of oil and gas concentration. Hao Qingfang et al. [5] discussed the wind speed migration law of oil and gas diffusion of the outer floating roof tank seal ring through numerical analysis and experimental verification. It was found that the high-diameter ratio affects the eddy current motion trajectory, and when the leakage hole is on the floating plate, oil and gas on both sides of the floating roof The concentration is higher than the upper and lower wind sides. Huang Weiqiu et al. [6,7] used CFD to simulate the diffusion of oil and gas in the inner floating roof tank, and found that the closer the floating disk is to the bottom of the tank, the faster the evaporation rate; the static pressure on the windward side of the tank body is higher than the leeward side and the tank walls on both sides, and the wind speed is against oil and gas The distribution influence is small, and oil and gas are prone to gather in the gaps between the floating disk and the tank wall. Jie Fang et al. [8] established a numerical simulation method for the wind field and gas content field of multiple oil storage tanks. It was found that when the wind speed is greater than 2m/s, the vapor concentration in the leeward area of the rear tank is higher than between the two tanks, which is easy to reach the explosion limit. The number of oil storage tanks makes the superposition effect of oil and gas in the downwind direction more obvious.

To sum up, there are countless studies on the diffusion of dangerous gas leakage in numerical simulation. A large number of research on the diffusion of oil and gas leakage in oil storage tanks by domestic and foreign scholars is mainly on the influence of oil and gas leakage and diffusion in a single oil storage tank without a safety bottom protection system in the case of seal ring failure and pore size leakage, and on the basis of Further research is still needed to study the impact of oil and gas leakage and diffusion caused by large external floating roof oil storage tanks equipped with safety bottom protection systems. To this end, Tao Jing[1] has used the large external floating roof oil storage tank equipped with a safe bottom protection system as the research object to numerical simulation of the oil and gas leakage caused by dangerous working conditions. Its oil and gas leakage diffusion law provides a theoretical basis for the prevention and control of fire accident risks of large external floating roof oil tanks equipped with safety protection bottoming systems.

2. Composition and Introduction of Floating Roof Safety Bottom Protection System

By installing new equipment above the floating tray of the outer floating roof oil storage tank, the nitrogen circulation and oil and gas emissions during the lifting and lowering of the floating tray are optimized, ensuring the safe operation of the oil storage tank and the smooth entry and exit of the oil. The main equipment includes 2 telescopic bladder sleeves and 12 devices composed of ventilation valves and air collecting covers, which are connected to a closed-loop system through DN100 stainless steel gas collecting pipes. The gas phase space below the floating disk is connected and formed into a closed gas collection environment. Among them, the new device plays an important role in the smooth operation of the floating disk. Its function is that when the floating disk drops to the bottom of the tank, the automatic ventilation valve cover is opened, allowing nitrogen to flow and inject into the space below the floating disk through the telescopic bladder, pipeline system and air collection hood to eliminate negative pressure, so that the oil products in the tank are Can be pulled out. On the contrary, before the floating disk floats, when the oil tank enters liquid, the mixed oil and gas between the floating disk and the liquid surface can be discharged through the automatic ventilation valve. After being collected through the air collection hood and the pipeline system, it will be collected from the two telescopic capsules. Concentrated discharge.

2.1. Equipment composition and functions

Telescopic capsule (2 pieces): function: adapt to changes in the lifting height of the floating disk, ensuring the continuity of nitrogen and oil-containing nitrogen flow. Installation position: above the floating disk, distributed symmetrically. Material: corrosion-resistant and high temperature-resistant elastic material to ensure long-term use. Ventilation valve and air collector (12 sets): Function: During the lifting and lowering of the floating disk, the circulation of nitrogen and oil and gas is automatically adjusted to ensure the airtightness of the gas phase space below the floating disk. Installation position: Floating disk edge, evenly distributed. Material: Stainless steel, corrosion resistant. DN100 stainless steel gas collection pipeline: Function: Connect all ventilation valves and air collectors to form a closed-loop system to ensure smooth gas circulation. Installation position: above the floating disk, arranged in an annular shape. Material: Stainless steel, corrosion resistant.

The schematic diagram of the specific installation location of the equipment is shown in Figure 1.

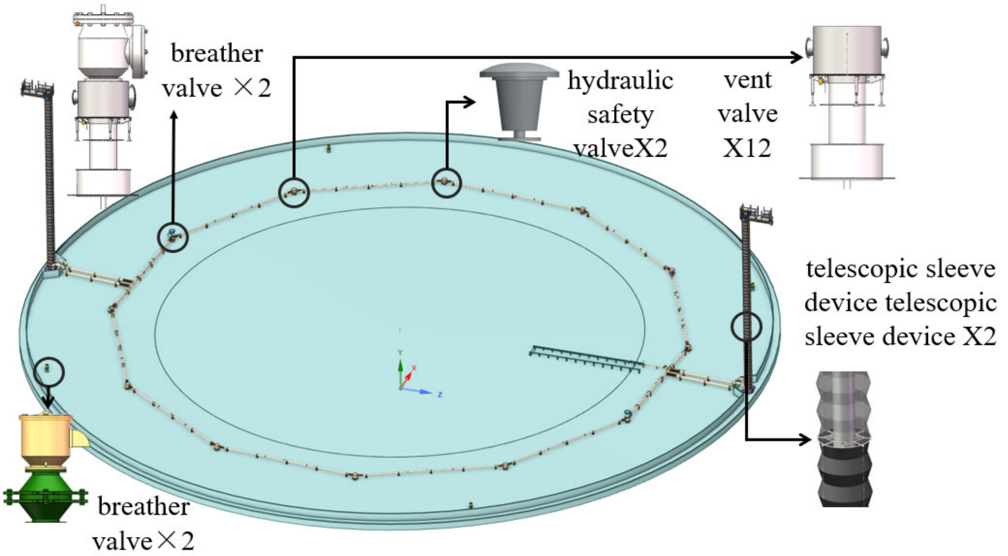


Figure 1. Floating top structure diagram[1]

2.2. Protection system composition

The bottom protection system is mainly composed of gas collection system, pipeline system, analysis and control device, field protection device, liquid nitrogen tank truck, mobile oil and gas recovery device, vent tower, etc. For details, please see the document [1].

3. Description of Hazardous Working Conditions and Numerical Simulation Methods

When the oil storage tank changes from the bottom vacant period to the bottom oil collection period, as the oil product is quickly injected into the tank, the oil-containing nitrogen gas is recovered through the pipeline system. If the recovery pipeline is cut off at this time, the large amount of oil-containing nitrogen gas inside is only When it can be discharged through the two breathing valves above the floating roof, severe oil and gas leakage and diffusion will occur over time. Now, the oil and gas leakage and diffusion under this dangerous operating conditions will be analyzed through numerical simulation methods. A schematic diagram of dangerous working conditions is shown in Figure 2

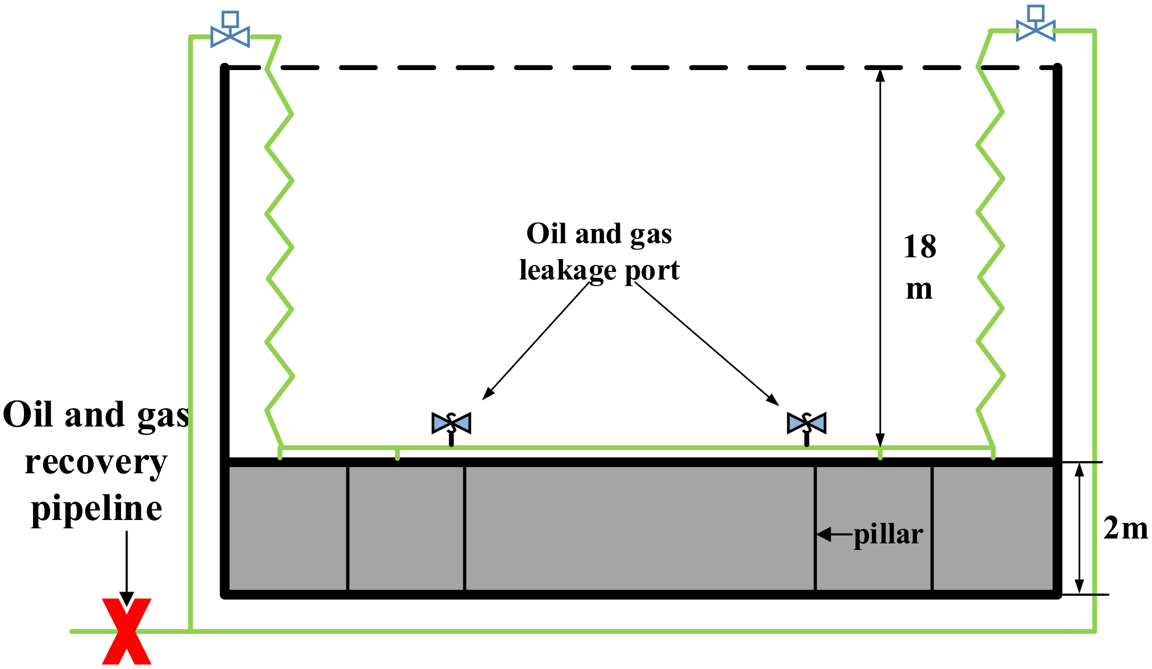


Figure 2. Dangerous working conditions diagram

The storage medium gas of crude oil storage tanks is a multi-component volatile organic substance. The leakage and diffusion of the oil storage tanks is a very complex heat transfer and flow problem and cannot be solved through a specific mathematical model. Using numerical methods, the flow characteristics of fluid in atmospheric turbulence can be accurately reflected. The basic principle of computational fluid mechanics FLUENT software is to numerical solution of the differential equations that control fluid flow to obtain the discrete distribution of the flow field of the fluid flow on the continuous region. Its simulation results are close to actual experiments and have been increasingly widely used.

3.1. Control differential equations and turbulence model

Oil and gas leakage diffusion is the process of diffusion of volatile organic matter (VOCs), and the main component of VOCs is C3-C5. As the main component of oil and gas diffusion, propane has similar physical properties to VOCs (density, viscosity, diffusion coefficient, etc.). To simplify the calculation, propane is simulated as a single component in the oil and gas diffusion process.

The diffusion of oil and gas components is described by a single-phase multi-component transport model. Therefore, the main control equations of this flow include the continuity equation, the conservation of momentum equation, the conservation of energy equation, the component transport equation and the turbulence equation.

1) Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{1}$$

In the formula, ρ is the density of the mixed gas, kg/m3; x_j corresponds to the movement in the three directions of x, y and z, respectively; u_j is the velocity component in the three directions of x, y and z, respectively, m/s.

2) Conservation equation of momentum:

$$\frac{\partial\left(\rho u_j\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\mu_t \frac{\partial u_i}{\partial x_j}\right)+(\rho-\rho_a)g_i \tag{2}$$

In the formula, p is the absolute pressure, Pa; μ_t is the dynamic viscosity of the fluid, Pa·s; ρ_a is the air density, kg/m^3; g_i is the gravity acceleration component in the three directions of x, y, and z, m/s^2.

3) Energy conservation equation:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j T)=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_c}\frac{\partial T}{\partial x_j}\right)+\frac{C_{P_v}-C_{P_a}}{C_P}\left[\left(\frac{\mu_t}{\sigma_c}\right)\frac{\partial \omega}{\partial x_j}\right]\frac{\partial T}{\partial x_j} \tag{3}$$

In the formula, T is the temperature of the fluid, K; σ_c is the turbulent Schmitt number, usually 1.0; ∂T is the turbulent Plande number, usually 0.9~1.0; *Cp*, *Cpa*, and *Cpv* are the fixed pressure specific heat capacity of the mixed gas respectively , the fixed pressure specific heat capacity of air (*Cpa*=1.005 at room temperature) and the fixed pressure specific heat capacity of leaked oil and gas *Cpv*=3, kJ/(kg·K); ω is the mass fraction.

4) Component transport equation:

In this simulation study, the chemical reaction between oil and gas and air is not considered, so the component conservation equation without chemical reaction is used:

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\omega\right)=\frac{\partial}{\partial x_j}\left(\rho D_1\frac{\partial\omega}{\partial x_j}\right) \quad (4)$$

Where D_1 is the turbulent diffusion coefficient, m^2/s; D_l=6.75e-6 m^2/s.

5) Turbulence model:

According to the concentration change characteristics during oil and gas leakage diffusion and reflecting the actual working conditions of oil and gas diffusion, this paper adopts the RNGk-ε turbulence model that introduces turbulent flow velocity and turbulent pulsation length parameters. This model can simulate the turbulent flow caused by the settlement of gas under gravity. In theory, it can also simulate the transmission of turbulent kinetic energy and the turbulent flow of gas in complex terrain, which has higher convergence and accuracy for the separation of fluid flow.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-\gamma_M+S_k \quad (5)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (6)$$

In the formula, μ is the dynamic viscosity, Pa.S; ρ is the fluid density, kg/m^3; k is the turbulent kinetic energy, m^2/s^2; ε is the turbulent dissipation rate, m^2/s^2; G_k is the turbulent flow generated by the laminar flow velocity gradient Kinetic energy; Gb buoyancy generation term; γ_M represents the compressibility correction term; $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are empirical constants and $C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.92, $C_{3\varepsilon}$=0.09; σk and σε are corresponding to turbulent kinetic energy k and dissipation rate ε, respectively The Plund number, where ∂k =1.0; $\partial\varepsilon$ =1.3; S_k, S_ε user-defined.

3.2. Geometric model and boundary conditions

Factors such as the gas collection pipes of the new home decoration above the floating roof, the telescopic bladder sleeves on both sides, local components and external conditions inside the floating roof tank will affect the simulation results. It will be more cumbersome if the numerical simulation is completely based on the actual structural dimensions. Poor convergence. Therefore, this paper simplifies the model based on actual conditions in Figure 3.

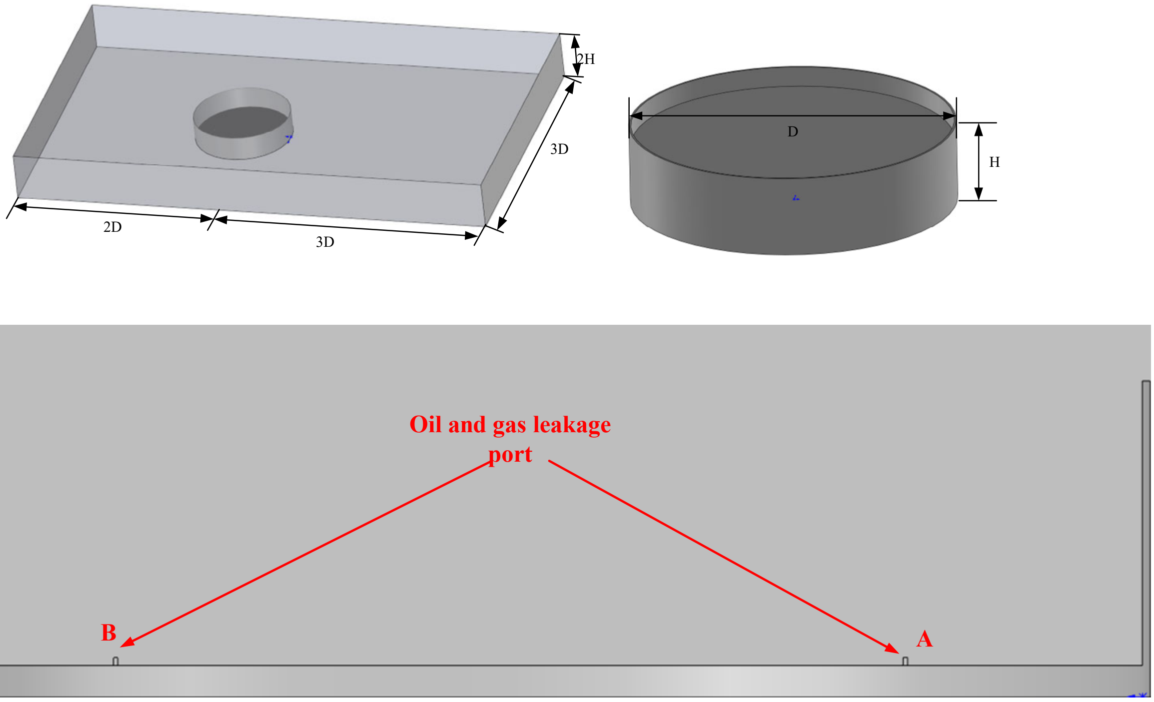


Figure 3. Geometric Model

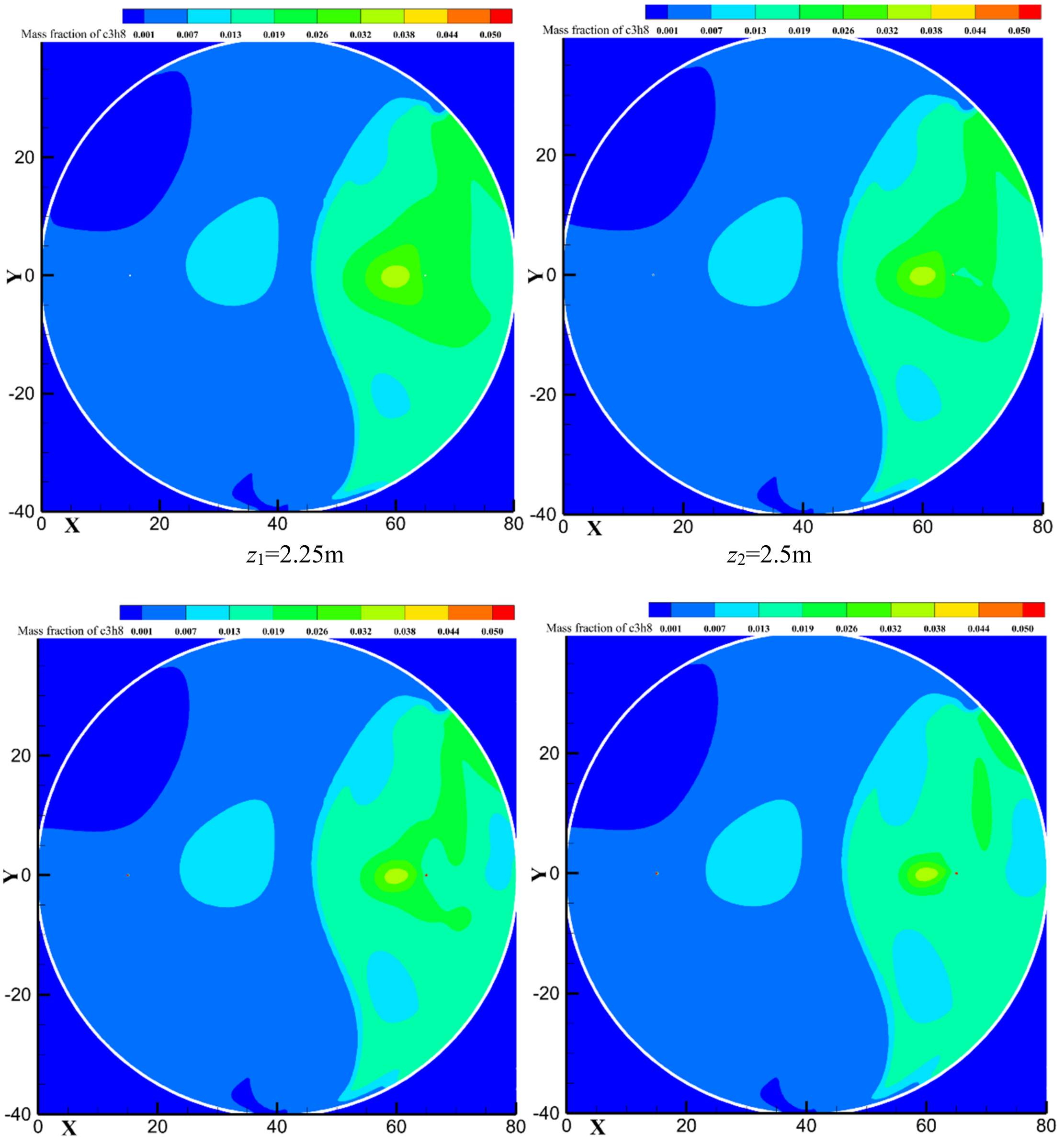
Using CFD software, a three-dimensional model of the outer floating roof tank was established in a ratio of 1:1, as shown in the figure. The calculated domain size is 400m×240m×40m, the diameter of the oil storage tank is 80m, the height of the tank is 22m, the external wind direction is in the positive direction of the -x axis, and the wind blows outward to the floating roof tank in a certain direction, causing the upper space of the floating disk and The change in the pressure difference around the tank wall is turbulent flow and is described by the k-ε turbulence model. The boundary conditions and initial condition parameters of the model are set as shown in Table 1.

Table 1. Setting of boundary conditions and initial parameters

Boundary Condition	Boundary Setting	Initial Condition	Parameter Setting
Calculate the entry on the left side of the domain	Speed entrance	Wind speed	2m/s
(Right exit)	(pressure outlet)	temperature	300*K*
Calculate the top and front and back sides of the domain	Symmetrical boundaries	Atmospheric pressure	101325Pa
Tank walland Floating deck and calculation domain bottom	Fixed wall surface	Turbulence model	k-ε model
Oil and gas leakage port	Speed entrance	Leakage speed	14.5m\s

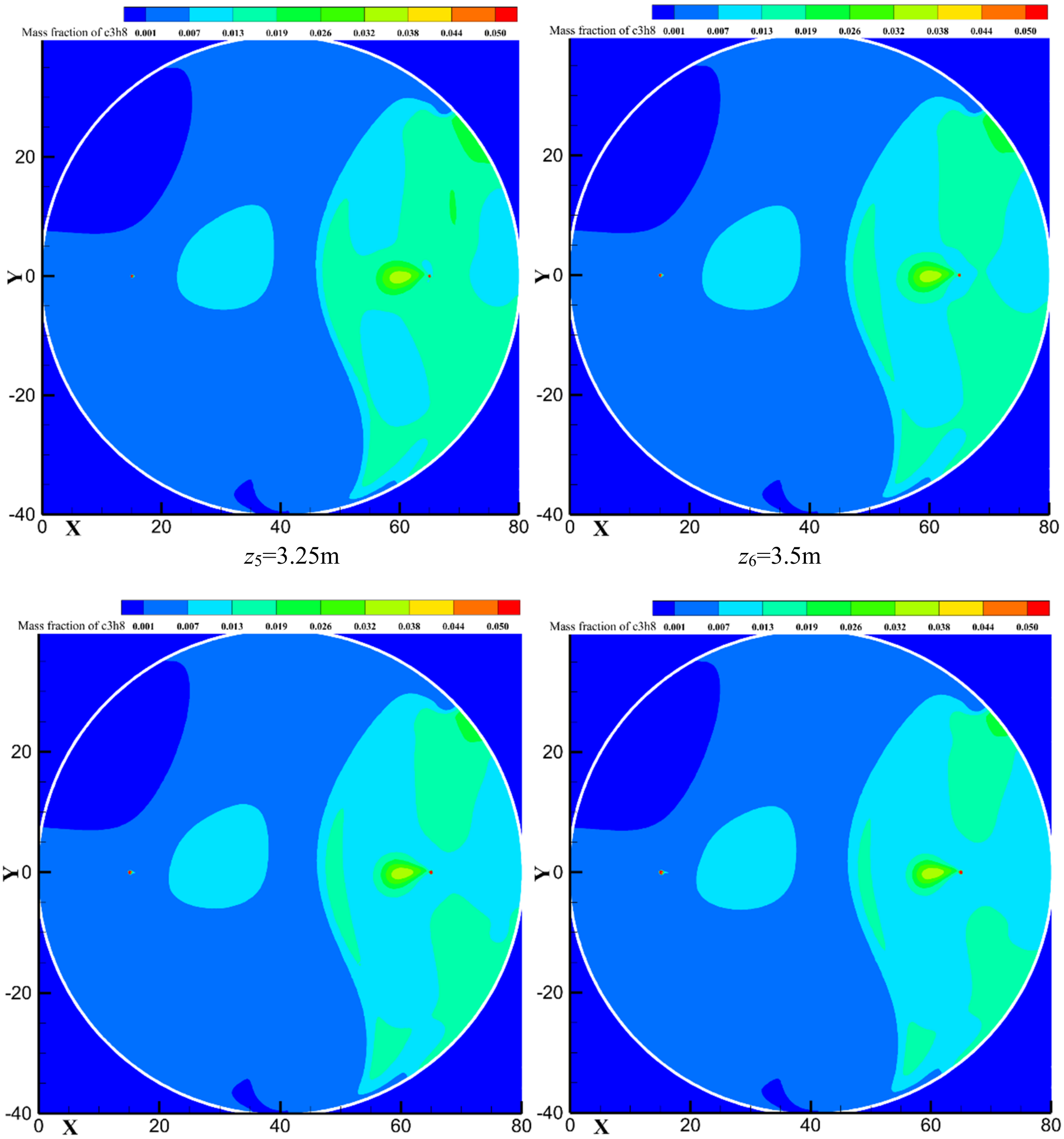
4. Simulation Results and Analysis of Oil and Gas Leakage and Diffusion

According to the simulation results, the diffusion stability stage of 500 seconds after oil and gas leakage was selected for analysis. A cross-section was taken every 0.25m along the *Z* direction of the inner diffusion space in the tank (Z_x=2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75 and 4m in total (Z_x =2.25, 2.5, 3.75 and 4m) Eight sections), as shown in Figure 4.:



z_1=2.25m z_2=2.5m

z_3=2.75m z_4=3m



z_5=3.25m z_6=3.5m

z_7=3.75m z_8=4m

Figure 4. Oil and gas concentration distribution in each height section within the control area

It can be seen from Figure 4 that the concentration of oil and gas around the leakage port B is much higher than that of leakage port A. After the high-speed oil and gas inside the oil storage tank is leaked out from the breathing valve, some oil and gas are exhausted due to kinetic energy and the density of oil and gas is higher than that of The air will diffuse downward with the gravitational potential energy and gather above the floating roof, and another part of the oil and gas will diffuse to the inner edge of the oil storage tank and above the oil storage tank with the internal wind speed flow field. A large amount of oil and gas gathered above the floating roof is not easy to diffuse with the internal flow field. As the leakage time accumulates, the oil and gas concentration reaches the lower limit of the oil and gas explosion concentration, making oil and gas explosion accidents very likely. Therefore, with B leakage port as the center coordinate, take the average oil and gas concentration at 4 points at ±X=5m and ±Y=5m to obtain the oil and gas volume fraction of the space above the floating roof with the height of the control area (z=2-4m) The changes are shown in Figure 5

From Figure 5, it can be seen that the average oil and gas concentration value within a radius of 5 meters at the leakage port B in the control area increases with the increase of the height above the floating roof, which also conforms to the oil and gas diffusion law in the tank analyzed above. And according to SY/T5225-2019 "Technical Regulations on Fire Protection and Explosion Safety Production Safety Regulations" of Petroleum and Natural Gas Drilling, Development, Storage and Transportation": One of the conditions for fire in the pipeline in the oil tank area is that the oil and gas concentration in the tank area should be lower than the explosion limit. 25%. The oil and gas concentration values at these heights inside the storage tank are all higher than 25% of the lower explosion limit, which can be judged as a hazard warning area. The oil and gas concentration values will increase over time, making it very easy to cause explosion hazard accidents.

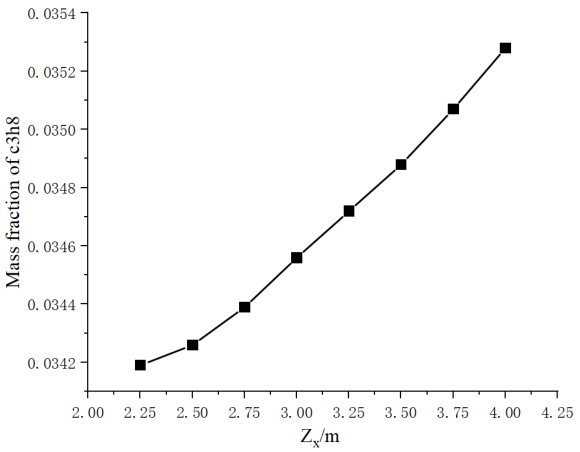


Figure 5. Changes in oil and gas concentration with height within the control area

In order to explore the relationship between oil and gas concentration in the internal control area of the storage tank and leakage time, set the maximum leakage speed and the external wind speed are 2m/s, and the data of oil and gas concentration at 0-500s at Z=2.5m are selected to make Figure 6.

From Figure 6, it can be seen that the oil and gas leaked from 100-300s diffuse from high places to 2.5m under the action of self-weight and flow field. The oil and gas concentration begins to slowly increase with time. At 300-500s, the oil and gas concentration increases rapidly with time. At 450 seconds, the oil and gas concentration has exceeded 50% of the lower explosion limit and has been determined to be a dangerous operation area. Measures should be taken immediately to eliminate the hazardous source.

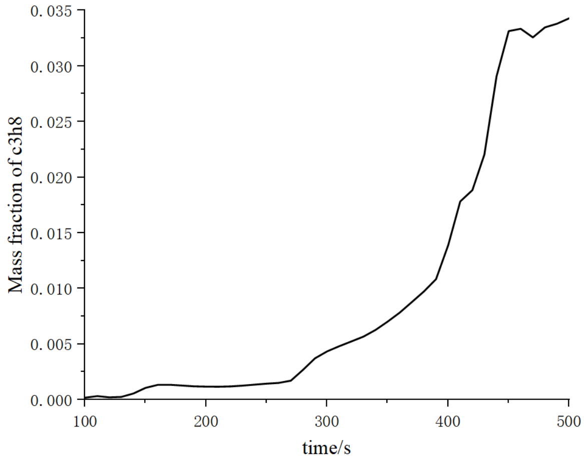


Figure 6. Curve of oil and gas concentration with time at cross section Z=2.5m

5. Conclusion

(1) This large external floating roof oil storage tank safety bottom protection system occurs in oil and gas leakage accidents under dangerous working conditions. When the leakage speed is 14.5m/s and the external wind speed is 2m/s, the oil and gas will be concentrated with the influence of self-weight and flow field. On the left side of the tank, and the oil and gas concentration around the leakage port B is significantly higher than the leakage port A, and the oil and gas accumulated above the floating roof is not easy to spread. As time accumulates, the concentration will reach the lower limit of explosion, which is very easy to cause explosion accidents.

(2) This large external floating roof oil storage tank safety bottom protection system occurs in oil and gas leakage accidents under dangerous working conditions. When the leakage speed is 14.5m/s and the external wind speed is 2m/s, the leakage time is between 100-300s. The concentration rises slowly; it rises rapidly at 300-500s, and at 450s, the concentration exceeds 50% of the lower limit of the explosion. Entering the dangerous operation area, measures need to be taken immediately to eliminate the dangerous source.

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