Numerical simulation of thermal radiation distribution of large-scale crude oil storage tank

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Abstract. When the fire of a large-scale crude oil storage tank occurs, the fire source will emit large heat radiation which can induce not only serious economic losses, but also casualties. This paper investigated the influence of full-surface fire occurring in a crude oil storage tank on the adjacent tanks by numerical simulation based on the fire dynamic simulation software (FDS). Firstly, the combustion model of 10^5 m^3 crude oil storage tank was constructed to reproduce the evolution behavior of the flame and smoke after the fire of the storage tank. The distributions of temperature and heat radiation value of adjacent storage tanks of crude oil storage tank were analyzed. The results show that a warning line with a radius of 57.77 m should be established to reduce the personnel and equipment damage caused by heat radiation when a full-surface fire occurs in the storage tank. This research can provide a technical basis and decision-making reference for the check computation of the fire-fighting capacity of fixed fire-fighting facilities, tactical arrangements of fire-fighting and rescue, and emergency rescue.

1. Introduction
In recent years, with the development of the petrochemical industry, the oil reserve systems in China have been continuously improved, and the construction of oil reserves and large-scale storage tanks have reached an unprecedented high. Large crude oil storage tanks (i.e. the volume of a single tank is greater than 50,000m^3) have many advantages compared to small oil tanks, such as smaller footprint per unit volume, lower cost, and easier management. Therefore, oil tanks tend to be larger and more intensive. However, for the large tank areas, the tank after an accident easily leads to catastrophic consequences due to the chain effect of events. If the fire source is not controlled in time in the central area of the explosion, the adjacent storage tanks will be heated and easily form secondary explosions. Additionally, the heat radiation intensity of the fire is very large, which not only brings serious economic losses, but also results in significant casualties.

It is necessary to study the combustion characteristic of large crude oil storage tanks. The full-scale storage tank fire experiment is one of the research methods. However, this method not only consumes a large amount of human and financial resources, but also has great safety hazards and environmental pollution. Therefore, many scholars attempted to use numerical simulation technology to construct crude oil storage tank models and collect various parameters in the combustion process of the storage tank to study tank fire [1-3]. Computational fluid dynamics (CFD) techniques have been utilized to simulate fire accidents and study the temperature field, oxygen concentration and other fire parameters [4-8].
Femga [9] optimized the heat radiation model of pool fire using CFD, which laid the foundation for the analysis of the pool fire thermal radiation through CFD. Alizadehattar et al. [10] used FLUENT to establish a heat radiation model of pool fires caused by organic matter to predict the safe spacing between the pool fire and its surrounding structures.

Subsequently, some researchers established a heat radiation model of LNG pool fires through FLUENT, and analyzed the change of LNG pool fires with time and the flame surface temperature and thermal radiation intensity of LNG pool fires with different diameters [11,12]. Che [13] applied three-dimensional numerical simulation to study the thermal response process of the tank under fire pool fires and jet fire conditions, and the simulation results showed that under the pool fire condition, the wall temperature reached 530°C within 300s, and the tank failed within 460s. Gabriele Landucci [14] used finite element analysis to simulate the thermal response process of atmospheric pressure storage tanks under long-distance pool fire conditions. The results showed that the maximum wall temperature of the 17480 m³ tank of is 450°C under the heat radiation of 450 kW/m². Hyundai et al. [15] used ANSYSCFX-11 to establish an organic peroxide pool fire model to predict the instantaneous temperature and heat radiation intensity distribution of the flame.

At present the research on the influence of the fire occurred in large crude oil storage tanks on the adjacent storage tanks is not enough. Therefore, in this paper, we used fire dynamic simulation (FDS) techniques to simulate the full surface combustion process of a 10⁵m³ crude oil storage tank. On this basis, the evolution behavior of the combustion was studied, and the temporal and spatial distribution of typical physical parameters such as temperature and heat radiation value of the adjacent tank is revealed. This study can provide a technical basis and decision-making reference for the check computation of the fire-fighting capacity of fixed fire-fighting facilities, tactical arrangements of fire-fighting and rescue, and emergency rescue.

2. Numerical simulation method

2.1. Brief of FDS Software

The FDS software, first developed in the United States, is one of fire dynamics software. It can simulate fire, smoke generation and spread based on the combustion model, fluid dynamic model and heat radiation model. The combustion problem of large crude oil storage tanks can be analyzed by utilizing this software. In this work, the volume of the large crude oil storage tank was set as 10⁵ m³.

2.2. Model Setup

The diameter of the 10⁵ m³ crude oil storage tank is 80 m and the height is 21.88 m. According to China's current GB50074-2002 Oil Tank Design Specification, the fire separation distance between 10⁵ m³ crude oil storage tanks should be 32 m. Since the cylindrical module cannot be directly added in the FDS, the multiple cuboid module is used to approximate and simulate the cylindrical oil tank. The model is shown in Fig.1.

Figure 1. 10⁵ m³ crude oil tank model in FDS.

Figure 2. Meshed models in FDS.
This model adopted multiple meshing. According to the FDS meshing principle, a grid with the length, width and height of 2 m can be used for the area between the two tanks. For other large spaces, a meshing method with the length, width, and height of 4 m is adopted, and the number of meshes is 423,000. The meshed model is shown in Fig. 2.

2.3. Fuel and fire source setting
The key parameters of the fuel and fire source are set as follows.

- **Burning velocity of the fuel.** According to relevant experimental studies, the linear burning velocity of crude oil is generally less than 4 mm/min. The density of the crude oil used in this simulation is 890 kg/m³, and the mass burning rate was chosen to be 0.059 kg/(m²·s).

- **Thermophysical properties of crude oil.** Crude oil is a mixture, and the thermal physical properties of crude oil from different producing areas vary greatly. In actual engineering, it is necessary to choose appropriate thermophysical data according to the specific crude oil. In this paper, the selected thermal physical properties of crude oil are as follows: mass burning heat is 47500 J/g; thermal conductivity is 0.15 W/(m·K); specific heat capacity is 2.4 kJ/(kg·K); mass density is 890 kg/m³; maximum mass burning rate is 0.059 kg/(m²·s).

2.4. Thermal radiation detector setting
This work focuses on the influence of the full-surface fires in crude oil storage tank on adjacent tanks. Therefore, the heat radiation flux detectors are arranged on the side of the adjacent tank facing the burning tank and on the entire floating roof surface. Due to the symmetry of the tank itself, the detectors are only placed on one half of the tank to reduce calculation load. The arrangement of the detectors is shown in Figure 3. Specifically, on the side facing the burning tank, the detectors are set with 20 columns, and the interval of each column is 2m. The number of detectors in each column is 11 from top to bottom with interval of 2m. On the floating roof surface, the probes are set with 11 groups with interval of 4m. The probe spacing in each group is also 4m. In this model, a total of 393 thermal radiation detectors were installed, as shown in Figure 3. Since crude oil is a highly flammable substance, after the storage tank is ignited, the flame on the surface of the oil will spread rapidly, forming a full-surface fire with stable combustion. In order to more fully understand the situation after the combustion of large crude oil storage tanks, the simulation time are set to 1800s.

![Figure 3. Display of heat radiation detectors.](image-url)
3. Results And Discussion

3.1. Heat release rate
Heat release rate (HRR) is an important parameter to measure the severity of fuel combustion. It represents the amount of heat released by the fuel combustion per unit time. The higher the HRR, the more intense the combustion, the more energy released per unit time, and the greater the impact on the surrounding environment. Fig. 4 shows the heat release rate with time. It can be seen from Fig. 4 that the whole surface fire progresses very rapidly, the HRR of the flame rises extremely fast and reaches the maximum HRR in about 3s and keeps a stable state with $1.4 \times 10^7$ kW after 20s.

![Figure 4. Relationship between heat release rate and time.](image)

3.2. Flame shape and smoke distribution
Fig. 5 shows the flame shape with time. It can be seen that during the combustion process, the flame is closer to the surface of the liquid pool, and the angle of inclination is large, up to 51.57°. Due to the influence of the southeast wind, the flame is torn and stretched continuously, and the flame flickering is frequent. The average flame height is between 55m and 60m, up to 83.39m. When the combustion reaction progresses, the flame surface is blown to an approximate horizontal angle by the strong wind, and the inclined flame tail has a great influence of the heat radiation on the downwind tank.

![Figure 5. Flame shape with time.](image)
Fig. 6 shows the smoke shape with time. The mass of the smoke is mainly concentrated around the storage tank, and the smoke mass concentration of the smoke at the top of the storage tank is low due to the full development of combustion. In addition, the mass fraction of the smoke at the top of the adjacent tank is relatively large because of the southeast wind, and as the reaction progresses, the smoke completely covers the adjacent tank.

![Fig. 6. Smoke shape with time.](image)

3.3. Temperature distribution
When a full-surface fire in a large crude oil storage tank occurs, a pool fire will be formed. In order to observe the influence of the burning tank on the adjacent storage tank, we selected the temperature slices at 56m, 76m and 96m away from fire source center, as shown in the Fig. 7. After the fire occurs, the flame will be jump with the wind, and the surrounding temperature will be affected. The temperature drops sharply after 300s, but gradually rises after 1200s. Therefore, in the long run, the temperature of the adjacent tank is relatively stable because of the continuous combustion of the large tank. With the increase of the distance away from the fire source, the temperature also drops significantly (see Fig.8).

![Fig. 7. Temperature slice settings.](image)

![Fig. 8. Temperature curve with time.](image)

The temperature near the fire source is relatively high, up to 1000°C, and the temperature field is inclined to the downwind direction due to the southeast wind. At the distance of 56m away from the fire
source center (the top of the adjacent tank), the temperature is not attenuated, still about 1000°C. At the distance of 76m away from the fire source center, the temperature decays faster, and the maximum temperature is about 370°C. At the distance of 96 m, the maximum temperature is about 270°C (see Fig.9). It can be seen from the temperature field that the temperature is decreasing horizontally. In the vertical direction, with the increase of the distance from the fire source center, the high-temperature region moves upward continuously.

Figure 9. Temperature distribution in the north-south direction of the fire source center (X is the distance from the center of the fire source)

3.4. Thermal radiation distribution
Radiant heat flux (RHF) is usually used to describe the magnitude of heat radiation intensity. It means the radiant energy on per unit area at per unit time (kW/m²). Fig.10 shows the heat radiation distribution of adjacent tank wall. It is found that the RHF of the adjacent tank tends to be stable after 20 s. Therefore, the average value of the RHF after 20 s is selected as the RHF of the adjacent tank. It can be seen from Fig.10 that when a full-surface fire occurs in a 10^3 m³ crude oil storage tank, the heat radiation intensity of the adjacent storage tank decreases from top to bottom. The radiation intensity near the fire is relatively large.

Figure 10. Thermal radiation distribution of adjacent tank wall.
The heat radiation range of the tank wall is 0.56-28.78 kW/m². Fig. 11 shows the heat flux of the tank wall in the horizontal direction. In the figure, 1-11 represent 11 rows of detectors along the OA direction in Fig. 10. It is found that the heat flux is largest near the fire source. With the increasing distance away from the fire source, the heat radiation on both sides of the tank wall decreases in turn, and the bottom of the tank receives less heat radiation than the top, as shown in Fig. 11. Fig. 12 shows the heat flux of tank wall in the vertical direction. In this figure, 1-21 represent 21 columns of detectors, respectively, along the OB direction in Fig. 10. It is can be seen that the first column of thermal radiation near the fire source is significantly larger than others. With the increasing distance from the ground, the heat flux first increases and then is stable. The maximum heat flux is at 16-17m from the ground, as shown in Fig.12.

Fig. 13 shows the influence of the heat radiation on the top of the tank. In this figure 1-11 represent the 11 rows of detectors, respectively, along the OA direction in Fig.10, and 1-21 represent the 21 columns of detectors, respectively, along the OB direction in Fig. 10. The radiation distribution decreases in a stepped manner from west to east, and the radiation intensity is highest at the front end of the floating roof surface.

Figure 11. Tank wall heat flux in the horizontal direction.  
Figure 12. Tank wall heat flux in the vertical direction.
Fig. 14 shows the heat flux distribution of the floating surface along the east-west direction. The heat flux value of the surface of the floating plate near the tank is 1.4-23.6 kW/m². With the increasing distance away from the fire source, the heat flux decreases continuously. Fig. 15 shows the heat flux value distribution of the floating surface along the north-south direction. With the increasing distance away from the center of the surface of the floating plate, the heat flux value also gradually decreases. According to the symmetry of the tank, the heat flux value of the full tank top increases first and then decreases with the increasing distance from the center.

**Figure 14.** E-W heat flux value of the floating surface.  
**Figure 15.** N-S heat flux value of the floating surface.

### 3.5. Fire control cooling water system

#### 3.5.1. Warning line setting.
As the fire progresses, the flame angle becomes larger and the flame is elongated, which increases the risk of heat radiation hazards to the persons staying at the downwind area.
According to the above analysis, the upwind area is relatively safe, but the heat flux value in the downwind area has exceeded 7 kW/m² within the red line of the burning tank (see Fig. 16). 7 kW/m² is the maximum threshold that can be withstood by firefighters with protective measures. Therefore, during firefighting and rescue, firefighters should avoid to enter this area and a warning line should be set up with a radius of 57.77 m.

Figure 16. Influence distance of heat radiation.  Figure 17. Movable firefighting water gun setting.

3.5.2. Movable firefighter water gun setting. After a full-area pool fire occurs in a large crude oil storage tank, it will have a direct impact on adjacent storage tanks. Due to the high temperature in the fire site and the risk of leakage and explosion, it is difficult for firefighters to get close to the burning tank. Therefore, the adjacent tanks and surrounding facilities should be effectively cooled before extinguishing the fire. Generally, the downwind tanks and facilities directly affected by the heat radiation need to be first cooled by using the fixed cooling system of the tank itself. However, however, after tank explosion, the facilities usually fail. Therefore, the movable firefighter water gun is adopted to cool the adjacent tanks. The movable firefighting water gun system can greatly compensate for the lack of cooling capacity of the fixed firefighting system, and it has become a key factor in controlling the fire range. Such a cooling system generally consists of a certain number of fire hydrants outside the fire dike. Under the wind speed of 10m/s, the influence range of the heat radiation is very close to the fire dike, (see Fig.17) and the heat flux in the red circle in Fig. 17 is more than 7 kW/m². Therefore, the fire hydrants should be set at the two points that fall on the fire dike and lie on the straight lines which pass the center point of the adjacent tank and coincide with the red circle. The angle between the two lines that pass the points and the center of the adjacent tank is 75.62°. And the distance between these two points and the adjacent storage tank is more than 90m.

According to the General Technical Conditions of the Firefighting Gun, the water supply intensity of the water gun is set to 120 L/s, the maximum rated pressure is 1.2 MPa, and the horizontal rotation angle is between 112.37° and 142.19°. According to Technical Specifications for Fire Water Supply and Fire Hydrant Systems, it is known that the duration of cooling water is set to 4.0h for floating roof tanks, shelter room and semi-underground fixed roof vertical tanks, and 6.0h for ground fixed roof vertical tanks with a diameter of over 20 m.

3.5.3. Fire hose setting. While cooling the adjacent storage tanks, the water curtains should be laid around the burning tanks to prevent fire from spreading so that the firefighters can get close to the burning tank. The fire water curtain system has the ability of cooling and fire protection. The spray water hose (hereinafter referred to as fire hose) can uniformly spray the mist water under a certain water pressure, and form a "water wall" with a certain height, which can reduce the radiant heat, cool fire separation facilities, dilute the concentration of the toxic gas, and save the firefighters.

After a full-surface fire occurs in a large crude oil storage tank, the fire hose can lay around the burning tank, and the upwind fire truck supply water to the hose, which can form a barrier for blocking
the smoke and fire. Fig. 18 shows the specific setting of the fire hose. It should be laid in the vicinity where the heat radiation is 7 kW/m². According to the Design Code for Fire Protection of Petrochemical Enterprises, the supply water intensity of the floating roof tank should not be less than 2 L/(min·m²).

![Figure 18. Fire hose setting.](image)

The water supply pressure of the fire hose is determined by the water pressure resistance of the hose itself, while the water supply height is determined by the water supply pressure and the aperture. The main performance parameters of the water hose currently used for firefighting are shown in Table 1. It can be seen from the table that the water supply height of the Type-65 water hose can reach 10m when the working pressure is 1.0MPa and 8m when the pressure is 0.8MPa. These two pressures fall in the range of the normal water supply pressure of the fire truck. For Type-65, the water supply height also meets the requirements of the general chemical equipment and storage tanks.

| Type | Specification | Pressure (MPa) | Inner diameter (mm) | Spray height (m) | Length (m) |
|------|---------------|----------------|---------------------|-----------------|------------|
| 8    | 50            | 0.8            | 51.0                | 8               | 20—30      |
| 8    | 65            | 0.8            | 63.5                | 8               | 20—30      |
| 10   | 50            | 1.0            | 51.0                | 10              | 20—30      |
| 10   | 65            | 1.0            | 63.5                | 10              | 20—30      |

4. Conclusion

(1) Numerical simulation of the heat radiation distribution of the full surface fire of crude oil storage tanks was carried out by using FDS software. The three-dimensional distribution of the radiant heat flux around the flame were obtained, and the distribution of the heat radiation intensity received by the adjacent storage tanks was investigated.

(2) After a full-surface fire occurs in the crude oil storage tank, a large amount of smoke generated. Due to the influence of the ambient wind, the smoke mainly accumulates on the top of the adjacent storage tank. The dense smoke not only seriously affects the judgment of firefighter on the fire, but also increases the difficulty of rescue. In addition, the smoke contains a lot of toxic substances, which poses a threat to the life and health of firefighters.

(3) The heat flux at the distance (57.77 m) away from the fire center is about 7kW/m² which is the limit value that the firefighter can withstand. Therefore, during firefighting and rescue, a warning line should be set with a radius of 57.77m and persons (including firefighters) should avoid to enter this area to reduce the threat of heat radiation to the life and health of persons. At the same time, movable firefighting water guns should be used for cooling adjacent tanks. Additionally, fire hose should be laid outside the dangerous zone to help firefighters get close to the burning tanks, thus better extinguishing the fire.
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