Numerical Simulation of Large Crude Oil Storage Tank Fire under Various Wind Speeds

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Abstract. In order to analyse the influence of the wind speed on the fire characteristics and hazards of large crude oil storage tanks, this paper used the fire dynamics simulation software FDS to simulate the fire of a large crude oil storage tank under various wind speeds. The fire characteristics such as flame, smoke and temperature distributions of the tank under different wind speeds were studied. The thermal effects on the adjacent tank and the way that the firefighters cool the hazardous area were discussed. The results show that with the increase of the wind speed, the flame, smoke and temperature distributions shift and spread downwind. When tank fire occurs, the firefighters should set up movable firefighting water gun near the dangerous area and lay fire water hose to the burning tank and its neighbours, which provides a good preparation for the subsequent firefighting operation near the burning tank.

1. Introduction

With the rapid development of China's petrochemical industry and the completion of the strategic reserve of crude oil, the safety of large oil depots and large storage tanks has become more and more important. However, in recent years, fire and explosion accidents occur frequently in large-scale storage tanks, and these accidents often cause very serious losses. Compared to other types of fires, full-surface fires formed after a fire in a crude oil storage tank have the characteristics of high burning rate, high flame temperature, intense radiant heat and high challenge in safety assessment of the tank after fire. Moreover, the direction and magnitude of the wind often play a decisive role in the progress and spread of the fire. Once the fire becomes difficult to control, firefighters will encounter many difficulties in the process of firefighting and rescue.

Hence, many researchers have attempted to study the influence of wind speed on the combustion characteristics of large-scale full-surface fires [1-3] besides the combustion characteristics of large-scale crude oil storage tanks [4-8]. Syed [9] found that tank diameter, wind speed and wind direction play a great role in the progress of fire. Sinai [10] applied CFDS-FLOW3D to simulate the kerosene pool fire of 20m diameter under windy weather conditions, and found that the shape of the pool, the height of the dike and the surrounding turbulence can affect the shape of the flame tail. However, these studies on the effects of wind on tank fires are mostly concentrated in the range of regular wind speeds [11-13]. Some researchers have specifically studied the combustion characteristics and the effects of heat radiation of large-scale storage tanks under strong wind conditions [14]. But for different wind speeds, in particular, under windy and even strong wind conditions, there is little research on large-scale crude oil storage tank fires. Therefore, this paper used the fire dynamics simulation software FDS to investigate the
influence of the crude oil tank fire on the flame inclination angle, flame temperature distribution and adjacent storage tanks under different wind speeds.

2. Numerical simulation method
This paper uses FDS software for fire simulation analysis. The FDS software is one of the fire dynamics simulation software developed by the Institute of Building Fire Research of the American Institute of Standards and Technology. It solves fire simulation problems based on combustion models, fluid dynamic models and thermal radiation models. It mainly uses mass conservation equations, momentum conservation equations and the energy conservation equation to describe the distribution of fire parameters such as velocity, temperature, and concentration of smoke components at various points in space and its changes with time. A numerical method is used to solve a set of N-S equations describing the low-speed heat flow. This method focuses on the smoke flow and heat transfer process during fire, and it can be suitable for flow field analysis of low Mach number, and simulate fire and smoke generation, development and diffusion process.

2.1. Numerical model of FDS

2.1.1. Turbulence model. The FDS software uses large eddy simulation model for fire calculation. Large eddy simulation was developed in the study of turbulent flow. The basic idea is to select a filter width between the large-scale structure and the small-scale structure of the flow field to filter the governing equation, and divide all variables into large-scale quantities and small-scale quantities. The accuracy of the large eddy simulation results is very high given the appropriate sub-lattice mode. The above characteristics of the large eddy simulation model determine that the simulation result is a physical real transient flow field, which plays an important role in in-deep understanding of the flow field.

2.1.2. Combustion model. In FDS software, the turbulent combustion model can be divided into a mixed component combustion model and a finite chemical reaction velocity model. In the simulated fire scenario, if the fire thermal effect is just considered, the mixed component combustion model can satisfy the solution requirements. If the concentrations of smoke, CO₂ and CO generated in the fire need to be considered, the finite chemical reaction model will be introduced into the simulation.

2.1.3. Thermal radiation model. In the calculation of thermal radiation, the method used in fire dynamics simulation software is finite volume method modified by radiation transmittal equation of non-scattering gray body gas. In the thermal radiation equation, the thermal radiation intensity is related to the wavelength, and the solution method is similar to the finite volume method.

2.2. Mathematical model of large crude oil pool fire

2.2.1. Flame height. The flame height of a pool fire has two definitions: one is the height of the top of the columnar body composed of greasy and luminescent carbon particles, which can be observed by photography or by the naked eye; the other is the flame height when completely burned by 99% of the fuel vapor burns completely. This paper uses the first definition. When there is wind, it can be calculated according to the Thomas model [15]; when there is no wind, it is calculated according to the Heskestad equation [16].

2.2.2. Flame inclination angle. The flame will have a certain inclination angle under the force field. Some researchers used the line connecting the apex of the flame and the midpoint of the bottom to visually indicate the angle of inclination of the flame showing the circular motion [17]. In this paper, according to the definition of SFPE, the angle between the centreline of the oil pool plume and the vertical axis is considered to be the flame inclination angle of the oil pool combustion under lateral wind conditions.
3. Numerical model

3.1. Geometric model
A $10^5$ m$^3$ crude oil storage tank has a diameter of 80 m and a height of 21.88 m in China. According to China's current GB50074-2002 Code for Design of Petroleum Reservoirs, the fire separation distance among two $10^5$ m$^3$ crude oil storage tanks is 32 m. Since the cylindrical module cannot be directly applied in FDS, the cylindrical oil tank is approximated by a plurality of cuboid modules (see Fig. 1). Considering the influence of the boundary on the calculation result and the calculation cost, the calculation domain range selected in this paper is $360\times200\times200$m.

![Figure 1. 10^5 m^3 crude oil tank model in FDS.](image1)

![Figure 2. Meshed models in FDS.](image2)

3.2. Meshing
On the basis of the geometric model, under the premise of ensuring the calculation accuracy and the calculation cost, the structured grid of the calculation domain is set. This simulation adopts multi-area meshing. According to the FDS meshing principle, a grid with a length, a width and a height of 2 m, respectively, can be used for a region between two storage tanks. For other large spaces, the grid with a length, a width, and a height of 4 m is adopted, and the total number of meshes is 346,800.

3.3. Fuel and ignition setting
The thermal properties of crude oil were selected as follows: maximum mass burning rate is 0.059 kg/(m$^2$$\cdot$s); mass combustion heat is 47500 J/g; thermal conductivity is 0.15 W/(m$\cdot$K); specific heat capacity was 2.4 kJ/(kg$\cdot$K); mass density is 890 kg/m$^3$.

3.4. Boundary conditions
The adiabatic boundary conditions are selected for the tank wall and the ground. According to the calculation conditions, the open boundary conditions are used around the calculation domain under the windless condition. Under the windy condition, the left wall of the calculation domain selects the velocity inlet to describe incoming wind, and other walls adopt open boundary conditions. In terms of the setting of wind speed, it is divided according to the wind scale, as shown in Table 1. The wind speed of levels 1, 3, 4, 5, 7, and 8 are set to 0 m/s, 1.5 m/s, 3.6 m/s, 6 m/s, 10 m/s, 15 m/s, and 20 m/s, respectively. The wind blows from west to east.
| Wind Scale | Name            | Wind Speed (m/s) |
|------------|-----------------|------------------|
| 0          | Calm            | 0.0–0.2          |
| 1          | Light air       | 0.3–1.5          |
| 3          | Gentle breeze   | 3.4–5.4          |
| 4          | Moderate breeze | 5.5–7.9          |
| 5          | Fresh breeze    | 8.0–10.7         |
| 7          | Moderate gale   | 13.9–17.1        |
| 8          | Fresh gale      | 17.2–20.7        |

3.5. **Thermal radiation detector setting**

Since the geometry of the tank and the external boundary conditions are axisymmetric, the natural convective heat transfer characteristics of the crude oil in the tank are also symmetrical. Therefore, the detecting point just considers the half cylinder of the central section of the tank. The detecting points on the top of the tank are numbered as T11, T12, T21, and so on, where T denotes the top surface of the tank the first number represents the order of rows, and the second number represents the order of columns. the detecting points on the wall of the tank are numbered as S11, S12...S21, S22..., where S indicates the side of the tank, the first number represents the order of rows, and the second number represents the order of columns.

**Figure 3.** Display of heat radiation detectors.

4. **Results and discussion**

4.1. **Effect of wind speed on flame characteristics**

4.1.1. **Flame shape.** In the absence of wind, a large crude oil storage tank will release a large amount of heat after a fire. During the combustion process, the flame will jump, but the amplitude is not large. In the stable combustion stage, a large amount of air is involved, forming a strong pulsating mushroom-like plume with a flame length of 83.38m and the flame inclination of 0° (see Fig. 4).
Figure 4. Flame shape with time under no wind condition.

In windy conditions, the flame and smoke are inclined to the east, and with the increase of the wind speed, the flame inclination increases. When the wind speed are 1.5m/s, 3.6m/s and 6m/s, the inclination angles are 17.24°, 32.53° and 42.43°, respectively. When the wind speed is 20m/s, the flame is even parallel to the ground (see Fig.5).

Figure 5. Flame shape at different wind speeds at 1800s.

According to the flame shapes under different wind speeds, a positive relationship between the wind speed and the flame inclination angle was obtained (see Fig. 6).
4.1.2. Smoke distribution. Crude oil is composed of a variety of hydrocarbons and has a high carbon content. Therefore, a large amount of black smoke will generate if fire, and then the smoke covers the entire surface of the oil pool, meanwhile, a large amount of smoke particles exists above the oil pool, which can severely threaten the adjacent tanks. Fig. 7 shows the Smoke distribution at different wind speeds at 1800s. From Fig.7, it can be seen that when there is no wind, the flame mainly develops upwards, and the smoke moves vertically upwards. In the case of wind, the wind speed has a greater influence on the smoke, and even affects the adjacent tank. When the wind speed reaches 20m/s, the black smoke generated by the fire completely covers the surface of the adjacent tanks, posing a great threat to them.

4.1.3. Temperature distribution. When a crude oil storage tank fires, the ambient temperature above the storage tank rises rapidly, the temperature from the flame surface to the centre gradually rises, and the surface air is drawn along this direction. The high-temperature region is under the flame and decreases with the increase of the flame height. As the wind speed increases, the convective heat transfer intensity of the flame is increased, resulting in that the flame temperature is lower and lower, and the high-temperature region is gradually reduced. Taking the temperature of 1000°C as an example, the cross-sectional area of the region where the temperature is 1000°C when the wind speed is 20m/s is significantly smaller than that under the windless condition. In addition, the temperature distribution of the flame is shifted due to the wind, and the shape of the flame is also deformed. The larger the wind speed, the larger the deviation of the flame temperature distribution, and the more obvious the shape deformation.

Fig. 8 shows the temperature distribution at the distance of 96 m away from the fire source under different wind speeds. It can be seen that under the windless condition, the maximum temperature is 22°C at the distance of 96 m from the center of the fire source, while 35°C, 270 °C and 320°C under the wind speed of 3.6 m/s, 10 m/s and 20 m/s, respectively. With the increase of the wind speed, the high-temperature region slowly shifts to the adjacent tank.
4.2. Effect of tank fire and wind speed on adjacent tanks

4.2.1 Temperature distribution of adjacent tanks. After a full-surface fire occurs in a $10^5\text{m}^3$ crude oil storage tank, the smoke derived from the fire source will rise and spread along the wind direction. When the high-temperature smoke covers the adjacent storage tank, it may cause damage to the adjacent tank structure. So it is necessary to study the temperature distribution of the top and surrounding of the adjacent tank. In order to observe the influence of the burning tank on the adjacent tank, we selected the temperature slices at 56m, 76m and 96m away from the center of the fire source, as shown in Fig. 9.

Fig.10 shows temperature at different distance away from the fire source under different wind speeds. As the wind speed increases, the temperature on the top of the adjacent tank rises sharply. Under the windless condition, the fire has little effect on the adjacent storage tank, and the temperature above the top of the adjacent tank is between 20 and 23°C, which is close to the ambient temperature. At the wind speed of 6 m/s, the temperature on the top of the adjacent tank has reached 190°C, while at 20 m/s, the temperature is as high as 750°C. Thermal exposure is divided into six grades according to API 579, as shown in Table 2. When the wind speed is 6m/s, the coating on the roof surface of the tank will soften, and the strength and hardness of the materials are also affected. When the wind speed is up to 20m/s,
the high temperature smoke has a great influence on the roof structure of the tank. The material performance is drastically reduced, as well as the corrosion resistance.

![Temperature curve at different distance away from the fire source under different wind speed.](image)

**Figure 10.** Temperature curve at different distance away from the fire source under different wind speed.

**Table 2.** Guidelines for assessing fire damage effects.

| Temperature range (℃)       | Heat/Temperature effects                                                                 |
|-----------------------------|-----------------------------------------------------------------------------------------|
| T (Ambient temperature)     | • No significant impact                                                                  |
| 65~205                      | • Metal surface coating softens, melts, and fiber plastic foams.                         |
| 205~425                     | • Structural steels, stainless steels, solution annealed nickel alloys, non-heat treated  |
|                             |  titanium and zirconium alloys generally.                                               |
| 425~730                     | • Steel starting to oxidize, the thicker the scale the hotter the temperature.           |
| Over 730                    | • Heavily scaled steel may be distorted because of thermal stresses.                    |
|                             | • Long exposure to these temperatures may affect grain structure, properties and         |
|                             |  corrosion resistance of steels and stainless steels.                                   |
|                             | • Steel that is water quenched may harden and lose ductility.                           |
|                             | • All heat-treated or cold-worked materials may have altered properties.                |

The high-temperature region is not limited to the burning tank, and it also gradually moves toward the adjacent tank due to the wind. The edge of the roof of the nearest adjacent tank near the fire source is most affected. With the increase of the distance from the fire source center, the temperature gradually decreases, showing a stepped manner.

**4.2.2 Thermal radiation effects on adjacent tanks.** Radiant heat flux is usually used to describe the magnitude of heat radiation intensity. Its physical meaning is the radiant energy received per unit area per unit time, in kW/m². Under the condition with or without wind, the wall of the adjacent tank is oriented in the southeast direction, and the heat flux value decreases from west to east and increases from bottom to top, as shown in Fig.11. The heat radiation received by the floating roof of the adjacent
tank is distributed in a stepped manner, and the high heat radiation area is mainly concentrated on the western end of the floating roof near the fire center, as shown in Fig. 12.

![Figure 11. Heat radiation distribution of adjacent tank wall (10m/s).](image1)

![Figure 12. Heat radiation distribution on the float roof surface of the adjacent tank.](image2)

![Figure 13. Heat flux value on the float roof surface of the adjacent tank under different wind speeds.](image3)
Fig. 13 shows the heat flux value on the float roof surface of the adjacent tank under different wind speeds. It is found that the heat radiation value near the center of the fire source is the largest. On the one hand, as the distance from the center of the fire source increases, the heat radiation intensity will decrease. On the other hand, as the wind speed increases, the high heat radiation area will first enlarge, and then decrease. Specifically, when the wind speed is in the range of 0-10 m/s, the heat radiation intensity increases, and the maximum heat radiation is 23.65 kW/m² under the wind speed of 10 m/s. But when the wind speed is up to 20 m/s, the maximum heat radiation drops to 18.8 kW/m². Therefore, there is a wind speed to maximize the peak of the heat radiation intensity.

4.3. Fire control cooling water system

4.3.1 Warning line setting. With the increasing of the wind speed, the flame inclination angle will become large and the flame will be elongated, which not only affects the adjacent storage tanks, but also increases the heat radiation risk of the downwind persons. Fig. 14 shows the Influence radius of heat flux value of 7 kW/m² under different wind speeds. It can be seen from the figure that as the wind speed increases, the radius of influence of heat radiation exceeding 7kw/m² is also enlarged, where 7kw/m² is the maximum threshold that can be withstood by firefighters with protective measures. Therefore, the warning lines with different radius should be set according to different wind speeds. For instance, when the wind speed is 20m/s, the influence radius is as high as 60.04m. That means firefighters should avoid to enter this area during firefighting and rescue. Meanwhile, the warning line with a radius of 60.04m should be set up.

![Figure 14. Influence radius of heat flux value of 7kW/m² under different wind speeds.](image)

4.3.2 Movable firefighting 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, 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, as shown in Fig.15.

When the wind speed is equal to or greater than 3.6 m/s, the heat radiation generated by the ignition tank will gradually affect the adjacent tank, and the heat flux in the red circle (see Fig. 15) will be equal to or greater than 7 kW/m². Therefore, the fire hydrants can 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 (see Fig. 15). The angle between the two lines that pass the points and the center of the adjacent tank is 63.1°. Under the wind speed of 10m/s, the angle between the two straight lines is 75.62°, while under the strong wind of 20m/s, the angle is 80.46°. It is found that with the increase of the wind speed, the angle between the two straight lines is also increases, as shown in Fig.16.

![Figure 15. Fire hydrant setting.](image)

![Figure 16. Variation of inclination at different wind speeds](image)

In the actual situation, the distance between the fire hydrants and the center of the adjacent storage tank is greater than 80m. According to the General Technical Conditions of the Firefighting Gun, the water supply intensity of the firefighting gun can be set to 80 L/s, under strong wind condition, the distance is greater than 90m, and the water supply intensity should be adjusted to 120 L/s, and the maximum rated working pressure is 1.2 MPa. At the same time, the horizontal rotation angle is set between 117.51°~148.5° according to the actual situation. From the Technical Specifications for Fire Water Supply and Fire Hydrant Systems, it is known that the duration of cooling water is set to 4.0 h for floating roof tanks, shelter room and semi-underground fixed roof vertical tanks, and 6.0 h for ground fixed roof vertical tanks with a diameter of over 20 m.

4.3.3 Fire hose setting. The fire water curtain system has the ability of cooling and fire protection. The spray water 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 the large crude oil storage tanks, the fire hose can lay around the fire tanks, and the upwind fire truck supply water to the hose, which can form a separation water curtain for blocking the smoke and the fire. The fire hose is arranged in a semi-circle manner at a periphery where the heat radiation value of the fire tank is greater than or equal to 7 kW/m². For instance, when the wind speed is less than 3.6m/s, the fire hose can be laid around the storage tank in a ring shape (see
Fig. 17). This way has a remarkable cooling effect because the ignition tank is fully surrounded by water curtain. When the wind speed is greater than or equal to 3.6 m/s, the influence of the ignition tank on the adjacent tank becomes obvious. The firefighters are not easy to lay the fire hose near the ignition tank. So, the fire hose can be adjusted to a semi-circle shape (see Fig. 18). According to the Safety Code for Design of Petrochemical Enterprises, the firefighting cooling water supply intensity of the floating roof tank should not be less than 2 L/(min·m²).

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 10 m when the working pressure is 1.0 MPa and 8 m when the pressure is 0.8 MPa. 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      |

5. Conclusion
The wind speed will affect the flame, smoke, temperature and heat radiation intensity of the tank fire. Specifically, the wind will cause the flame and smoke to incline downwind, and the inclination angle has a positive relationship with the wind speed. Additionally, the wind speed will cause the flame temperature distribution to deviate to the downwind direction and deform.

The wind speed has a great influence on the temperature distribution of adjacent storage tank. Under strong wind conditions, the high-temperature area will be transferred from the edge of the adjacent tanks to the center. Meanwhile, the temperature will rise sharply, and it has a positive relationship with the wind speed. However, the heat radiation received by the adjacent storage tank does not increase continuously with the wind speed. When the wind speed is within 0-10 m/s, the heat radiation intensity increases, but when the wind speed is 20 m/s, the overall heat radiation intensity is significantly lower than that at 10 m/s. This indicates that the heat radiation intensity at a certain fixed point is not linearly positively correlated with the wind speed.

7 kw/m² is the maximum threshold that can be withstood by firefighters with protective measures. Therefore, under the wind speed of level 1, level 3, level 4, level 5, level 7, and level 8, the warning...
lines with the radius of 49.12 m, 52.24 m, 55.51 m, 57.77 m, 58.78 m, 60.04 m, respectively, should be set up. At the same time, the fire hose and movable firefighting water gun should be used for better cooling effect, which can provide a better way for firefighters to save the firefighting time.

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