Numerical Simulation and Risk Analysis on Large-Scale Oil Tank Farm Conflagration Based upon FDS

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Abstract: With regard to the oil characteristics of volatility and fluidity, safety issues may occur in case of oil tank leakage, conflagration and even explosion. In this thesis, the fire dynamics simulator (FDS for short) was used to simulate the conflagration of a 5000m³ floating-roof oil tank. By simulating and calculating the oil tank conflagration, it obtained the effect of the distribution principle and the ambient wind speed in the thermal radiation field on the distribution principle in the radiant heat field. In comparison of the heat flux failure criteria at home and abroad, the safe intensity threshold between adjacent oil tanks was analyzed when the conflagration occurs on single oil tank. Then it came to a conclusion that, latent risk exists in current domestic fire separation distance 0.4D, which couldn’t meet the safety requirement on adjacent oil tanks. Meanwhile, it analyzed the distribution principle of the radiation thermal field in single floating-roof oil tank conflagration, and obtained the minimum safety distance of adjacent oil tanks at various ambient wind speeds, thus providing reference standards and scientific proof for designing safe tank farm as well as controlling the danger sources.

1. Introduction

The oil is a kind of volatile and fluid substance, so once it leaks from the damaged oil tank, safety issues such as conflagration and explosion will take place. What’s worst, in the midst of oil tank conflagration, burning oil will run everywhere and the fire source will rapidly expand to the whole area within the fire walls, thus bringing about sharp increase of fire power. In such case, the burning oil tank must be put out in the first place; hydro-cooling must be done on the surrounding buildings and equipment so as to minimize the conflagration loss. Or else, in case that individual oil tank is on fire, it may probably cause the adjacent oil tanks to burn and explode, accordingly bringing about serious casualties and great economic losses. Therefore, it is a burning issue to probe into the process simulation of conflagration in oil tank farm and its energy transmission rule.

This thesis calculated and analyzed the outcome of floating-roof oil tank conflagration by means of numerical simulation. It acquired the effect between the upper wall temperatures of adjacent oil tanks. In accordance with the burning characteristics and the distribution principle of thermal radiation, along with the thermal radiation failure criteria, the thesis clarified the risks of oil tank conflagration then provided reference standards and scientific proof for designing safe tank farms as well as controlling the danger sources.

2. FDS Parameter Settings

Developed by the National Institute of Standard and Technology (NIST) in America, the FDS
application used large eddy simulation technology in calculation and its results have been proved by quite a few experiments. With the analysis of FDS simulation, it obtained the burning mechanism in oil tank conflagration and the destructive radiation scope of oil tank flame. As a result, it can provide guidance for the developing process of oil tank conflagration as well as the design specifications of the safety distance between oil tanks.

It has some difficulty to implement the numerical simulation of large-scale oil tank conflagration. A collection of parameters including the heat release rate of the fire source, the radiation percentage, the carbon black generation ratio and else are supposed to be set appropriately. Moreover, it should select rational extended area and grid precision to calculate the effect of smoke resistance on the thermal radiation.

2.1. Heat Release Rate
A great deal of experimental study indicated that, for pool fire, the conflagration which diameter is less than 0.1m can be named as the laminar flow region; which diameter stays between 0.1m and 0.5m is called transition region; and that of diameter above 1m is turbulent region. On the other hand, the combustion rate of the pool fire increases as its diameter enlarges, which however to a certain extent, its combustion rate per unit area goes to a constant value. Figure 1 showed the scale correlation of combustion rate (the decreased height below the surface of using liquid fuel) and flame height with the oil pool diameter. These data were acquired from the experimental research by Blinov and Khudyakov[1].

![Figure 1. The scale correlation between the burning rate and flame height of pool fire and the diameter of oil pool](image)

The heat release rate of pool fires can be calculated out by below formula [2]:

\[ HRR = \frac{mph}{60} \]

(1)
m refers to the linear combustion rate; \( \rho \) refers to the density of oil fuel and \( h \) as the net heat of fuel combustion.

Shown in Figure 1, various fuels possess different combustion rates. Nevertheless, when the diameter of oil pool increases to certain level, the respective combustion rate inclines to a ceiling value which doesn’t increase even if the diameter continues to enlarge. It is generally agreed that, if the diameter of oil pool is larger than 10m, the oil tank combustion rate per unit area has reached the limiting value.

2.2. Settings of Carbon Black Generation Ratio
Carton black generation is a significant factor that affects the radiation heat transfer. Meanwhile, it directly interferes with the simulating precision of temperature distribution. High-temperature carbon black is also one of the important thermal radiation sources. The radiation model of carton black participates to reduce its temperature distribution. In FDS application, the generation ratio of carbon black is directly set in the light of experience and experimental data. Then its simulating yield is
obtained by multiplying the coefficient by the heat release rate. Regarding large-diameter oil tanks, the carbon black generation ratio can be set as 0.1 in accordance with the experience.

2.3. Radiation Percentage
The “smoke resistance effect” on flame and the radiation of environment amplifies as the diameter of oil tank enlarges. In the calculation of small-scale combustion, the default radiation percentage in FDS radiation model is 0.35. In case the diameter of oil tank increases, its radiation percentage should be smaller. Many relevant experiments have disclosed the principle: The percentage of losses on environmental radiation caused by pool fire flame may change as per the diameter of oil tanks. It was shown in Figure 2:

Figure 2. Variation rule of the percentage of ambient radiation loss from pool fire flame with diameter

It is shown in Figure 2 that, in case the diameter (D) of the pool fire is relatively smaller, it can approximately consider the heat loss percentage of environmental radiation that is caused by fire source as a constant value; It will not change with changes of the diameter (D). Normally, if D≤2m, it can be regarded that the radiation percentage Xr≈0.35; if D>2m, Xr∝αD⁻⁰·⁵. In the formula, α is a constant coefficient. Through experiments by Japanese scholars, when the diameter of pool fire reaches 20m, its radiation percentage Xr is 0.16.

2.4. Settings of Grid Size
In the midst of using FDS software to implement numerical simulation on the process of conflagration, to achieve relatively more favorable fitting between the calculated results and the experimental results, the grid size at fire source and nearby area is supposed to be controlled within 0.05 – 0.1D*. Relatively thicker grid can be used at further area from the fire source. The maximum size of grid can be 0.5D*. In this expression, D* represents the characteristic fire diameter, which is mainly related to the heat release rate of fire source[^3].

\[
D^* = \left( \frac{\dot{Q}}{\rho C_p T_g g} \right)^{\frac{1}{2}}
\]  

(2)

3. Simulation on a 5000 m³ Floating-Roof Oil Tank Conflagration
The floating-roof oil tank has a diameter of 22m and a height of 15m. It can reserve 5000 m³ crude oil. It width from the tank wall to the sealing ring is 1.33m, and the height of sealing ring baffle is 0.91m. Accordingly by calculation, with regard to the floating-roof oil tank, once the conflagration starts at the sealing ring, the flaming area \( S = \pi R^2 - \pi R_s^2 = \pi (11^2 - 9.67^2) = 27.5 \pi m^2 \); once open conflagration starts, the flaming area \( S = \pi R^2 - 121 \pi m^2 \).

3.1. Settings of Simulating Parameters in Conflagration
Pyrosim software was used to calculate the circumstances. It is shown in Figure 3:
Taking into account the influence on the calculated results as well as the limitation on computer resources from the extended area, the calculated area was determined as 40m×120m×60m. In addition, thermal radiation monitoring sites were installed at the height of 18m, 20m, 30m, 40m and 50m above the center of oil tank and the annular flame as well as at the positions of L/D=0.9, 1.0, 1.1, 1.5, 2.5, 3.5 and 4.5 with a height of 10m, 15m and 17m respectively.

1). Fire power: Regarding the annular fire source, its area is $27.5\pi m^2$, which can be approximately considered as equivalent to an oil pool of 10.5m diameter. It can calculate out the heat release rate per unit area as $2074MW/m^2$. And thus the fire power is about 180MW; as to a round open fire source with a diameter of 22m, its area is $121\pi m^2$. In accordance with the formula, it can also calculate out the heat release rate per unit area as $2074kW/m^2$ and the general fire power as 790 kW/m². This section concentrated on studying the security influence on the adjacent oil tanks once the oil tank conflagration developed continuously and steadily. Therefore, in the process of simulation, the development phases of oil tank conflagration was not considered, so its heat release rate was determined as a constant value at the very beginning of simulation.

2). Grid Division: In accordance with formula 2, it can figure out:

$$D = \left( \frac{\dot{Q}}{\rho_c C_p T_a \sqrt{g}} \right)^{\frac{3}{7}} = \left( \frac{180\times10^3}{1.29\times4.758\times300\sqrt{9.8}} \right)^{\frac{3}{7}} = 3.96 \approx 4$$

$$D = \left( \frac{\dot{Q}}{\rho_c C_p T_a \sqrt{g}} \right)^{\frac{3}{7}} = \left( \frac{790\times10^3}{1.29\times4.758\times300\sqrt{9.8}} \right)^{\frac{3}{7}} = 7.2$$

If the fire power is 180MW, the rational grid size near to the fire source will be 0.2m ~0.4m; the maximum grid size can be set as 2m at farther position. When the fire power reaches 790MW, its rational grid size alongside the fire source is 0.36m ~0.72m; and the maximum grid size can be set as 3.6m at farther position. After comprehensive consideration on the computing accuracy and efficiency, the grid size near the fire source of annular conflagration was chosen as 0.2m; and the grid size at extended area was selected as 0.4m; As to open conflagration, the grid sizes near the fire source and within the extended area were both set as 0.4m.

3). Radiation percentage: in accordance with the empirical formula, if $D>2m$, $X_r \propto aD^{0.5}$. Tested by the experimental data, the radiation percentage of the oil tank with a diameter of 20m is 16%. Thereupon when the equivalent diameter of annular conflagration is 10.5m, it can calculate out the radiation percentage as about 22%; when the equivalent diameter of open conflagration is 22m, its radiation percentage can be calculated as 15.3%.

4). Environmental parameters: For the experimental environment, the temperature was set as 20℃, the pressure was set as 101.3kPa, the relative humidity as 40% and the initial ambient wind speed as 0m/s. Besides, in considered of the open tank conflagration impact on surrounding thermal radiation field, the ambient wind speed was respectively set as 2m/s, 4m/s and 8m/s. which can be regarded as simulating the influence of level 2, 3, 4 or 5 wind speed on oil tank conflagration.

5). Thermo-physical parameters: The tank body is made of steel, which thermal conductivity is 49.8W/m*K and specific heat capacity is 0.47kJ/kg*K. The ground material is concrete, which thermal conductivity is 1.0W/m*K, specific heat capacity is 0.8kJ/kg*K, thermal diffusivity is 5.7E-&&
and material thickness is 0.2m.

6). Carton black generation ratio: as per experience, it was set as 0.1.

3.2. Simulating Results of Conflagration

The curve of fire source heat release rate was shown in Figure 4. As to the annular tank flame, its heat release rate fluctuated near 180MW; as to the open tank flame, its heat release rate fluctuated near 790 MW;

In the midst of conflagration simulation, the area which temperature stayed above 300°C was regarded as flame area. On the section x=0, the flame contours of both annular flame and open flame on top of the 22 m floating-roof oil tank were shown respectively in Figure 5 as below. From this figure, when the open flame ascends, its volume becomes greater.

The curve of the thermal radiation intensity from 10m, 15m and 17m height at a distance of 0.4 D from the oil tank was shown in Figure 6. It can be seen that, for annular flame, at the position of L/D=0.9 and H=17 m, the thermal radiation intensity is about 8.5kW/m². At the position of L/D=0.9 and H=15 m, the thermal radiation intensity is about 5 kW/m². On the ground level, the thermal radiation intensity was negligible. For open flame, at the position of H=17 m, the computed thermal radiation intensity was about 12 kW/m². At the position of H=15 m, the intensity was about 9kW/m².
and at the position of H=10 m, the intensity was only 3kW/m². The data showed that, for both annular flame and open flame, their intensity of received thermal radiation have reduced on the vertical direction from the top of oil tank to the ground.

![Figure 6. L/D=0.9 Thermal radiation intensity at 10m, 15m and 17m](image)

The L/D variation curves of the thermal radiation intensity from annular flame and open flame at H=17m position were shown in Figure 7. From this figure, the radiation intensity spiraled down as the horizontal distance enlarged. At the same horizontal position, all open flames released larger radiation intensity than the annular flames.

![Figure 7. the curve of thermal radiation intensity varying with distance at H=17m](image)

In case H=17 m, the thermal radiation intensity of open flame at various ambient wind speeds changed with the changes of distance. The correlation was shown in Figure 8. At the position of L/D=0.9 and H=17 m, the intensity of thermal radiation spiraled apparently as the wind speed increased: Specifically, the calculated intensity when the wind speed is 2 m/s increased by 16 kW/m², about 50% growth in comparison to that when the wind speed is 0m/s. When the ambient wind speed increases by 4m/s, the intensity grows to 24 kW/m²; again, when wind speed increases by 8 m/s, the thermal radiation intensity rises up to 30 kW/m².
3.3. Analysis on the Numerical Results

In China, the fire separation distance between large floating-roof oil tanks is specified as 0.4 D[4]. In the “Code for Design of Oil Depots” (GB-2002)[5], the Clause 6.0.5, was newly revised as: The fire separation distance between floating-roof oil tanks/inner floating-roof oil tanks are calculated as per 0.4 D which must be larger than 20 m. Under special circumstances, the minimum fire separation distance can be set as 20 m. However, it must accord with the Clause 12.1.7 Section 3 and the Clause 12.2.8 Section 4 in the regulations (Requirements for Fire Cooling System). In accordance with the fire code of “Standards on the Inflammable and Combustible Liquid” (NFPA30) issued by the National Fire Protection Association in America, it provided that, for tank farm which diameter is more than 45 m and which is equipped with fire dike, the fire separation distance should be 1/4 (D1+D2)[6]. In case the oil tanks possess the same diameter, the fire separation distance will be 0.5 D; In Japan, the fire code (Hazardous Articles Safety Precautions) provided that, the distance between Class A tanks must be 1.0 D[7].

The key factor of regulations on oil tank fire separation distance is to prevent the destruction effect of thermal radiation from burning oil tanks on surrounding objectives. The q ~ Q diagram of thermal radiation destruction was shown in Table 1.

| Hazard Category | Burn conditions of personnel | Destruction conditions of facilities |
|----------------|------------------------------|-----------------------------------|
| Hazard degree | Light burns | Serious burns | Death toll | Mild damage | Serious damage |
| Thermal radiation intensity | 4.0 kW/m² | 12.5 kW/m² | 25.0 kW/m² | 12.5 kW/m² | 25.0 kW/m² |

The capacity of oil tank is large so the duration of oil tank conflagration is relatively longer. Consequently, the heat flux criterion is frequently used in predicting the personnel injury around the oil tank as well as the damage and destruction of oil tank. By combination of currently using critical heat flux value, when it defines the fire separation distance between two adjacent oil tanks, their received thermal radiation should be less than 12.5 kW/m². Furthermore, the received thermal radiation for fire fighters should be no more than 4.0 kW/m².

The Figure 9 indicated that, the receiving thermal radiation at the height of 15m and 17m on the walls of adjacent oil tanks was about 5 kW/m² and 8.5 kW/m². According to present regulations on heat flux failure criterion and fire separation distance in China, in case annular conflagration occurs on single oil tank, it will not cause adjacent oil tanks to start fire or explosion, thus meeting the safety requirements;
Figure 9. L/D=0.9 thermal radiation intensity of annular fire at different heights

Shown in Figure 10, when the ambient wind speed was 2 m/s, the thermal radiation intensity at the height of 15 m and 17 m on the walls of adjacent downwind oil tanks both exceeded 12.5 kW/m². When the wind speed was 4m/s, the received thermal radiation intensity at the same locations apparently reinforced. It was up to 20 kW/m². And when the wind speed reached 8m/s, the received thermal radiation intensity had arrived at its maximum value, 30 kW/m². In such circumstances, 0.4 D of fire separation distance is far from enough for keeping the adjacent oil tanks from explosion or fires.

Figure 10. Measurement results of thermal radiation monitoring points under different wind speeds of open fire

By analysis, it found out that, in China’s present fire code on fire separation distance between oil tanks, 0.4D possesses latent risks. In case one floating-roof oil tank starts fire, under windy circumstances, the burning tank may pose a threat to its adjacent oil tanks. It was shown in Figure 11, by fitting the variation curves of thermal radiation intensity changing as per the changes of distance from the center of burning oil tank, it obtained a rational fire separation distance. In this case, the threshold of thermal radiation failure criterion was set as 12.5 kW/m².
4. Conclusions

After fitting the data and the calculations, when the safety threshold of heat flux failure criterion was chosen as 12.5 kW/m², it came to following conclusions:

1). After the burst of single oil tank conflagration, the acceptable intensity threshold of safe thermal radiation between adjacent oil tanks was provided by comparison of the heat flux failure criteria at home and abroad. The 0.4 D fire separation distance which was determined the domestic administration possesses latent risk. Therefore, it cannot meet the safety requirements on adjacent oil tanks.

2). In case the ambient wind speed is 2m/s, the fire separation distance is supposed to be at least 0.5 D so as not to compromise on the security of its adjacent oil tanks after the burst of single oil tank conflagration;

3). In case the ambient wind speed is 4m/s, the fire separation distance is supposed to be at least 0.7 D so as not to compromise on the security of its adjacent oil tanks after the burst of single oil tank conflagration;

4). In case the ambient wind speed is 8m/s, the fire separation distance is supposed to be at least 0.8 D so as not to compromise on the security of its adjacent oil tanks after the burst of single oil tank conflagration;

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