Research on thermal response of pool fire of oil tank based on PyroSim

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Abstract: This paper presents a numerical investigation aimed at studying the thermal response of adjacent tank caused by different fire conditions. The analysis involves two-step procedure:(1) PyroSim model to obtain the temperature and the inclination variation of the large pool-fire flame, to determine the ultimate temperature distributions of the target tank, and to compare the ultimate temperature and the fuel ignition temperature, thus to determine the target tank is safety or not,(2) There are three kinds of semi-empirical models for describing the radiation e.g.(i) point source,(ii) Shokri-Beyler and (iii) Mudan models, to determine thermal radiation flux of the target tank. The analysis considered the influence of two parameters: (i) seven kinds of wind, (ii) five kinds of distances between the tanks. The paper compares three kinds of semi-empirical models and PyroSim model, so PyroSim model is more fit for relationships between thermal radiation flux. The simulation results show that the maximum temperature of the target tank is the connection between the wall and the top of the tank; the target tanks have failure risk within 0.3D and 0.6D tank distances and the tank spacing greater than or equal to 0.9D have no failure risk.

1. Introduction

Large atmospheric storage tanks have the characteristics of large volume, concentrated distribution, flammability and explosion. The fire hazard is one of the main concerns associated with fuel storage tanks [1]. A pool fire occurred in the oil tank, and the strong thermal radiation effect of the ignited oil tank is easy to ignite the target tank, causing a large area fire in the tank area. Therefore, under the fire conditions of the entire surface of the oil tank, it is significant to study the thermal response and failure mode of the target tank for the evacuation of people and the fire rescue.

At present, many scholars have conducted a lot of research on the response process of the oil storage tank under fire, mainly focusing on the research of the flame structure of the oil tank fire, the radiation characteristics and the failure of the target tank. E.g., Che Wei [2] simulated the thermal response...
process of the internal temperature of the LPG storage tank under two different fire conditions. The results showed that the tank wall temperature reached 530°C at 300 seconds and the storage tank failed at 460 seconds. Valerio Cozzani [3] analyzed the thermal response process of 10 kinds of atmospheric pressure storage tanks smaller than 39 meters in diameter under the action of thermal radiation. The results show that when the radiation intensity is less than 15kW/m², the storage tank failure time is greater than 10 min and the radiation intensity is less than 10 kW/m², the storage tank failure time is greater than 30 min. Zong Hui [4] used ANSYS software to simulate the problem of the target tank being impacted by explosive debris. Li Yu [5] used Fluent software to simulate the influence of the diameter of the oil tank and the height of the tank wall on the thermal radiation distribution in the fire. Tschirschwitz [6] located and weighed the explosive fragments of liquefied gas tank in the pool fire environment of boiling liquid expansion steam explosion.

In view of the shortcomings of the existing research on the definition of the failure of target tank under fire conditions, the wind speed and the distance between oil tanks are combined to use PyroSim software to simulate the thermal response of the target tank under different working conditions. The paper pre-judge the failure of the next target tank, compare and analyze the simulation results with the calculation results of the semi-empirical model, provide a reference for the prevention, control and suppression of oil tank fires.

2. Pool-fire modeling

2.1. Model creation

Two vaulted oil tanks with the same size and material are selected as the research object, the left side is the source tank (ignition tank), and the right side is the target (target tank), as given in figure 1. The simulation area is a three-dimensional space, with length, width and height of 81m×32m×60m, V=5000m³, H₀=12.6m, D₀=22.7m, the tank wall material is SPV490Q steel, δ=6mm, and θ₀=15° [7].

2.2. Grid division

In order to achieve the best simulation accuracy, the length of the cell size in the three directions is preferably close [8]. Mesh the cuboid calculation area in the three directions of X, Y, and Z, and divide it into a grid of 1m×1m×1m, with a total of 155520 cubic small grids, and improve the operating efficiency of the software under the premise of ensuring simulation accuracy. The type of grid boundary vent is open.

| Nomenclature     | R       | linear distance between the point source and the target |
|------------------|---------|---------------------------------------------------------|
| V                | H       | flame height                                             |
| H₀               | d       | horizontal distance between the point source and the target |
| D₀               | A_f     | pool fire area                                           |
| δ                | ρ₀      | air density (1.16 kg/m³)                                 |
| θ₀               | g       | acceleration of gravity(9.8Kg/s²)                       |
| m_w₀             | D       | pool fire diameter                                       |
| ΔH               | U_c     | characteristic wind speed                                |
| HRR              | I       | thermal radiation flux                                   |
| c                | q''     | thermal radiation flux on the surface                    |
| ρ                | E       | thermal radiation flux on the surface of the pool fire flame |
| α                | F_view  | viewing angle coefficient                               |
| u_w              | F_v     | vertical viewing angle coefficient                       |
2.3. Parameter settings

The storage medium in the ignition oil tank and the target tank is gasoline, $m_0=0.055\text{kg/m}^2\text{s}$ [9], $\Delta H=4.61\times10^4\text{KJ/kg}$, $HRR=3280\text{kW/m}^2$, $c=1.83\text{kJ/kg/K}$, $\rho=684\text{Kg/m}^3$, and $\alpha=1000/\text{m}$ [10,11,12]. The flame combustion model uses the $t^2$ fire growth model [13]. There are 11 rows and 5 columns in the ignition tank thermocouple, and the row and column spacing are 3 meters. The thermocouples of target tank are arranged one every 2m from the top of the tank along the crossover line, with a range of 90° and 15° intervals for each group, as shown in figure 1.

2.4. Initial condition Settings

This paper simulates 35 kinds of fire scenes, including five kinds of separation distances between tanks $d=0.3D$, 0.6D, 0.9D, 1.2D, 1.5D and 7 kinds of wind speed $u_w=0-6\text{m/s}$. The ambient temperature set to 20°C, the ambient humidity set to 40%, the atmospheric pressure is 0.101MPa, and the filling factor is 80%. The fire type of the source tank is pool fire. The fire simulation time set to 1200 seconds.

3. Applications

3.1. Parametric study of flame

The numerical results presented the change of the temperature and the shape of the flame under 7 kinds of wind conditions and discussed the data of the thermocouple above the source tank, find the maximum value recorded by the thermocouple, make the trend line of the maximum temperature value of the flame $T_{\text{max}}$ change with the $u_w$ and get the closest regression fitting formula. The combined formula is $T_{\text{max}}=19.454\ln(u_w)+1013.4$, and the fitting degree is $R^2=0.9675$. As illustrated in figure 2, the maximum flame temperature of the igniting oil tank shows a logarithmic upward trend with the wind speed increases. The higher the wind speed, the more oxygen enters the combustion area, the more intense the combustion, and the higher the maximum flame temperature.

When the pool fire broke out, black smoke is generated due to insufficient entrainment of oxygen. The closer to the liquid level of the oil tank, the more air enters the bottom of the flame, resulting in a
visible flame. Figure 3(a) illustrates the inclination of the flame of the source tank under different wind speed conditions. In this paper, the flame inclination angle is analyzed with the visible flame part, the scatter diagram of the flame inclination angle $\theta$ with the wind speed $u_w$ is drawn, and figure 3 (b) illustrates the trend line of the flame inclination angle with the wind speed and obtains the relationship between $\theta$ and $u_w$: $\theta = -1.3571u_w^2 + 15.929u_w + 1.8571$, the fitting degree $R^2 = 0.9914$, the flame inclination angle changes with the wind speed in a parabolic pattern, become smaller gradually.

Figure 3(a). Variation of flame inclination.  
Figure 3(b). The angle ($\theta$) evolution obtained as a function of the wind speed($u_w$).

3.2. Thermal radiation distribution of target tank
Using PyroSim software to perform a pool fire simulation calculation on a 5000m³ gasoline storage tank. After analyzing the 35 scenarios, the temperature distribution map of the target tank wall found that: (1) The temperature of the target tank roof is significantly higher than other place, the top of the target tank close to the side of the source tank has a higher temperature, especially the surface temperature near the top edge of the source tank is the highest, as depicted in figure 4. (2) The wind speed will cause the flame of the source tank to tilt, affecting the temperature of the target tank body. (3) The separation distance between the tanks affect the thermal radiation dose received by the target tank and the temperature of the target tank.

Figure 4. Maximum temperature distribution of the target tank roof.
In order to better analyze the relationship between the maximum temperature of the target tank and the wind speed, a trend line is added to the scatter diagram of the wind speed and temperature, the wind speed and the maximum temperature of the target tank are in a logarithmic relationship, as shown in figure 5. When the highest temperature of the target tank body is greater than the autoignition temperature of the medium in the oil tank, it is defined as the failure condition of the target tank. The autoignition temperature of gasoline is 298.9°C [14]. When the maximum temperature of the target tank body exceeds 298.9°C, the oil tank is considered to be invalid. Figure 5 illustrates the separation distance between tanks is 0.3D, and the $u_w=0-6m/s$, all target tanks have failed. When the separation distance between tanks is 0.6D and the $u_w=0-1m/s$, the target tank has not failed; $u_w=2-6m/s$, the target tank has failed. When the separation distances between tanks are 0.9D, 1.2D, 1.5D, and the $u_w=0-6m/s$, the target tanks are in a safe state.

![Figure 5. Relationship between wind speed ($u_w$) and maximum temperature ($T_{tm}$) on target tank.](image)

3.3. Thermal response of target tank at 0.3D

The separation distance between tanks equal to 0.3D, no matter what wind conditions, target tank has failed, so choose $d=0.3D$ to analyze the thermal response of target tank. Figure 6 (a) illustrates the relationship between the temperature of the hottest point of the target tank with time under different wind speeds within 1200 seconds. The trend of the seven curves is similar in different wind speeds. The temperature of the target tank wall gradually rises with the increase of time. In the initial stage of the fire, the temperature of the target tank is lower, the amount of heat loss is smaller, and the temperature rises faster. As the time of the fire continued, the external radiation energy of the tank wall gradually increased, the temperature rising trend gradually slowed down and eventually stabilized. However, due to different wind speeds, the time taken for the hottest point to reach the autoignition temperature is different, and the time for the hottest point temperature to stabilize is also different. The time for the hottest point to reach the autoignition temperature and the time for the hottest point to stabilize are both reduced as the wind speed increases, and the highest temperature that the hottest point can reach increases as the wind speed increases. Figure 6 (b) show a scatterplot of the wind speed ($u_w$) and the time (t) it takes for the hottest point of the target tank to reach the autoignition temperature for $d=0.3D$ cases. Figure 6 (c) show the scatterplot of wind speed ($u_w$) and the hottest point of the target tank to reach the maximum temperature ($T_{tm}$) for $d=0.3D$ cases.
Figure 6 (a). Temperature ($T_m$) change of the hottest spot of target tank with 0.3D separation distance between tanks within 1200s (t).

Figure 6 (b). The time (t) taken to reach the autoignition temperature as a function of wind speed ($u_w$).

Figure 6 (c). The change of maximum temperature ($T_{max}$) with wind speed ($u_w$).

The time for the hottest point of the target tank to reach the autoignition temperature decreases as the wind speed is increased, but the downward trend of the time for the hottest point to reach the autoignition temperature also gradually slows down as the wind speed increases. The time for the hottest point to reach the autoignition temperature is 600 seconds for $u_w=0$m/s. The time for the hottest spot to reach the autoignition temperature is 215 seconds for $u_w=6$m/s. The increase in wind speed increases the...
amount of thermal radiation received by the target tank, and the temperature of the target tank increases, accelerating the failure of the oil tank.

4. Available pool-fire semi-empirical models

4.1. Point source model
The point source model [15] assumes that the thermal radiation generated by the flame is emitted from a single point located at the three-dimensional center of the pool fire flame, that is at H/2 on the central axis of the flame. The point source model assumes that the 30% heat release rate of the pool fire burning spreads out in the form of radiant heat energy at the point source, and the thermal radiation flux (I) received by the target surface is considered as given by equation (1).

\[ I = q R \sin \theta = \frac{0.3 q}{4 \pi R^2} \frac{H}{2 \left( \frac{H^2}{4} + d^2 \right)^{1/2}} \]  

(1)

The flame height [16] when there is no wind is considered as given by equation (3).

\[ H = 42D \left[ \frac{m_r^r}{p_0 (gD)^{0.5}} \right]^{0.6} \]  

(3)

Equation (4) indicates that the flame height in the wind.

\[ H = 52D \left( \frac{m_r^r}{p_0 (gD)^{0.5}} \right)^{0.67} \left( \frac{U_m}{D_c} \right)^{-0.21} \]  

(4)

4.2. Shokri-Beyler model
The Shokri-Beyler model [17] assumes that the thermal radiation generated by the flame is emitted from a cylinder of the same flame height, and the diameter of the pool fire is the diameter of the cylinder. The thermal radiation flux (q'') accepted by the target see equation (5):

\[ q'' = EF_{\text{view}} \]  

(5)

\[ E = 58(10^{-0.008} + 0.023D) \]  

(6)

\[ F_{\text{view}} = (F_v^2 + F_h^2)^{1/2} \]  

(7)

4.3. Mudan model
Mudan model [18] treats the pool fire flame as a vertical or inclined cylindrical radiation source. Considering the influence of environmental factors, the atmospheric transmission coefficient is added to the model.

The radiant heat flux (q'') received by the target is considered as given by equation (8):

\[ q'' = EF_{\text{view}} \tau \]  

(8)

\[ E = \frac{D m_r^r \Delta H}{D + 4H} \]  

(9)

4.4. Comparative analysis of different models
The point source model does not consider the effect of wind speed on the flame structure, so the three semi-empirical models are analyzed under no wind conditions. It can be seen from figure 7 that the
radiant heat flux received by the target point gradually decreases with the increase of the separation distance between tanks; the radiant heat flux received by the target point is calculated by the Mudan model with the largest result under the same separation distance, closely followed by the source model, and the Shokri-Beyler model is the smallest. The American Institute of Chemical Engineers stipulates that under uncooled conditions, the minimum thermal radiation flux received by target tank is specified as 13.5 kW/m² [19]. The isoline is shown in figure 7 and the Mudan model calculates the failure of target tank. The critical separation distance between tanks is between 0.6D-0.9D, the point source model calculates the critical separation distance between tanks for target tank failure is 0.6D, and the Shokri-Beyler model calculates the critical separation distance between tanks for target tank failure is 0.3 D. The PyroSim simulation results are between 0.6D-0.9D, which is the most similar to the Mudan model simulation results.

Zhang Longmei [20] pointed out that the Mudan model simulation results under wind conditions are more reliable than the point source model and the Shokri-Beyler model. Analysis of the Mudan model simulation results shows that the radiant heat flux received at the point also gradually increases as the wind speed increases, as shown in figure 8; when the separation distance between tanks is less than or equal to 0.6D, the target tank has failed under any wind speed conditions; the target tank fails after the wind speed exceeds 2 m/s for d=0.9D; the target tank fails after the wind speed exceeds 3 m/s for d=1.2D; the target tank is in a safe state for d=1.5D. The simulation results of the Mudan model are higher than those of the PyroSim model. The increase in wind speed causes more oxygen to enter the combustion area to intensify the combustion, which increases the flame temperature, and the increase in wind speed also strengthens the flame convection heat transfer, reduces the flame temperature, and the increase trend of the radiant heat flux received at the target should gradually slow down, so the PyroSim model can more accurately predict the changes in the radiant flux received by target tank.

Figure 7. Variation of target point thermal radiant flux (q’’) with separation distance (d) between tanks for uw=0m/s.
Figure 8. The change of thermal radiant flux ($q''$) received at the target point with wind speed ($u_w$).

5. Conclusion

1. Using PyroSim software to conduct a full-surface fire numerical simulation of a 5000m³ gasoline vault tank, the maximum flame temperature increases logarithmically, and the flame inclination angle changes parabolically with wind speed.

2. The thermal radiation dose received by the target tank decreases with the increase of the separation distance between tanks, and increases with the increase of wind speed. Under the conditions of different separation distances between tanks and different wind speeds, the junction of the target tank roof and the tank wall is the area with the highest temperature of the target tank.

3. When the temperature of the highest point of the target tank exceeds the autoignition temperature of the storage medium in the oil tank, the storage tank is deemed to be invalid. Increased wind speed or reduced separation distance between tanks will accelerate the failure of adjacent storage tanks. Under 7 wind conditions, target tank with separation distances between tanks of 0.3D and 0.6D have failed. The target tank with other separation distances between tanks have no risk of failure under simulated wind conditions. The target tank has failed under 7 wind conditions for $d=0.3D$, the shortest failure time is 215s.

4. In the absence of wind, the simulation results of the PyroSim model are most similar to the simulation results of the Mudan model. The calculation results of the point source model and the Shokri-Beyler model are relatively small; under the wind conditions, the simulation results of the Mudan model are compared with the simulation results of the PyroSim model. It is too high, so the PyroSim model is more accurate in calculating the thermal response of the tank fire.

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References

[1] M. Gómez-Mares, L. Zárate, J. Casal, (2008) Jet fires and the domino effect, Fire Saf. J. 43 (8) 583–588.

[2] Che Wei. (2009) Numerical simulation of thermal response of LPG storage tank in fire environment, Ph.D. Dissertation, Dalian University of Technology, 67-72.

[3] Valerio Cozzani, Alessandro Tugnoli,Ernesto Salzano. (2006) Prevention of domino effect: From active and passive strategies to inherently safer design[J]. Journal of Hazardous Materials ,139(2).

[4] Zong Hui. (2016) Study on the Failure Probability and Risk Evaluation of Storage Tank Groups in
the Tank Farm, Ph.D. Dissertation, Southeast University.

[5] Li Yu, Zhang Tao. (2018) CFD-based research on the heat radiation distribution of the entire surface of the oil tank fire [J]. Fire Science and Technology, 37 (01): 7-10.

[6] Rico Tschirschwitz, Daniel Krentel, Martin Kluge, Enis Askar, Karim Habib, Harald Kohlhoff, Simone Krüger, Patrick P. Neumann, Sven-Uwe Storm, Michael Rudolph, André Schoppa, Mariusz Szczepaniak. (2018) Experimental investigation of consequences of LPG vehicle tank failure under fire conditions [J]. Journal of Loss Prevention in the Process Industries.

[7] Fu, W.Q. (2014) Design Specification for Vertical Cylindrical Steel Welded Oil Tank [S], China Planning Press, Beijing.

[8] Shang Chao, Wang Keyin, Huang Haiying, Chen Yukun. (2013) PyroSIM-based fire tree modeling research [J]. Fire Science and Technology, 32 (09): 1030-1033.

[9] V. Babrauskas, Heat release rates, in: P.J. DiNenno (Ed.), SFPE Handbook of Fire Protection Engineering, third ed., National Fire Protection Association, Quincy, MA, USA, 2002.

[10] Guo Xin. (2017) Research on the strength of the cooling water of the adjacent oil tank under the fire environment of the oil tank, Ph.D. Dissertation, China University of Petroleum (Beijing).

[11] Fernanda da Silva Santos, Alexandre Landesmann. (2014) Thermal performance-based analysis of minimum safe distances between fuel storage tanks exposed to fire [J]. Fire Safety Journal, 69.

[12] Yao Zhongpeng, Wang Ruijun, Zhang Xijun. (1995) Heat Transfer Science. Beijing Institute of Technology Press, Beijing, 157 ~ 159.

[13] Liang Junhai, Li Xia, Lin Jianhui, Li Li, Liu Jizhu. (2014) PyroSim-based high-speed train fire analysis [J]. Journal of Chongqing University of Technology (Natural Science), 28 (10): 35-37.

[14] A.M. Kanury, (1975) Introduction to Combustion Phenomena, v. 2, CRC Press, New York, NY, USA.

[15] Y. Liu, (2011) Thermal Buckling of Metal oil Tanks Subject to an Adjacent Fire, Ph.D. Dissertation, University of Edinburgh, Edinburgh, Scotland.

[16] THOMAS P H. (1963) The size of flames from natural fires [C]. London: 9th Symposium on Combustion, Academic Press, 76-78.

[17] M. Shokri, C.L. Beyler, (1989) Radiation from larger pool fires, SFPE J. Fire Prot. Eng. 4 (1): 141-150.

[18] K.S. Mudan, (1984) Thermal radiation hazards from hydrocarbon pool fires, Prog. Energy Combust. Sci. 10 (1) 59–80.

[19] Huang Kun, Li Qin, Xu Jie, Kong Lingzhao. (2019) Research on the Influence of Wind Speed on the Thermal Radiation Distribution of Fire in Storage Tanks of Product Oil Depot [J]. Thermal Science and Technology, 18 (05): 386-391.

[20] Zhang Longmei, Jiang Pan, Lu Shunqing. (2015) Comparative analysis and research on the quantitative model of heat radiation of pool fires [J]. Industrial Safety and Environmental Protection, 41 (09): 58-61.