Study on multiple thermal radiation response of adjacent tanks based on numerical simulation

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Abstract. In order to obtain the time to failure of adjacent tanks under multi-thermal radiation conditions, the thermal response of gasoline tanks under multi-thermal radiation was studied. The heat radiation values of the adjacent tanks under pool fire were calculated. The temperature distribution and the corresponding stress of the adjacent tank were studied with ANSYS-Workbench software under the influence of single heat radiation and multi-thermal radiation. According to the physics properties of tank steel Q235B, the time to failure (ttf) of the tank was analysed. The results show that the temperature rise rate affected by the coupling effect of multi-thermal radiation is significantly higher than that affected by single heat radiation; when the storage tank is affected by the single heat radiation, the time to failure is about 22min; when the storage tank is affected by the coupling effect of multi-thermal radiation, the time to failure is about 15min.

1. Introduction
By the end of 2017, chemical companies accounted for about 7% of the total number of industrial enterprises in the country\textsuperscript{[1]}. There were 502 national key chemical parks or industrial parks with petroleum and chemical industry as the leading industry. There are many storage tanks in petrochemical companies, which store many flammable and explosive substances, especially prone to domino accidents. The escalation vector that triggers the secondary accident escalation are usually: heat radiation, overpressure and fragment projection. When multiple damage effects are coupled together, the failure probability of the target equipment will increase. Cozzani et al. fitted the expansion probability model of atmospheric and pressure equipment under heat radiation and put forward the ttf of atmospheric vessels considered is higher than 10 min for escalation threshold lower than 15 kw/m\textsuperscript{2}, and the ttf of pressurized vessels resulted higher than 10 min for the radiation intensity of 60 kw/m\textsuperscript{2} \textsuperscript{[2-3]}. Landucci et al. fitted a simplified expansion probability model by analyzing the time to failure of tanks under different thermal radiation models in case of fire\textsuperscript{[4]}. Xianfu Feng et al constructed the coupling model of thermal radiation shock wave debris in domino accident, and studied the most likely secondary accident combination and its probability of the target equipment using probability combination method \textsuperscript{[5]}. Fuzhen Chen et al. discussed the maximum possible propagation path of a tank fire accident, it was concluded that the probability of domino accident increased significantly when the tank was coupled by multiple heat radiation fields\textsuperscript{[6]}. 

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The thermal response process of the tank is related to the prediction of the time to failure of the tank, and it is an important parameter to evaluate the possibility of risk escalation. This paper will use the finite element simulation software ANSYS-Workbench to model the simplified model of container failure based on thermal nodes, and obtain the temperature change of the storage tank under the influence of single thermal radiation and thermal radiation-thermal radiation coupling. Based on this, the time to failure of tank is predicted.

2. Tank model selection
In this study, three tanks in an oil depot in Nanjing were selected as the research objects, and the changes in wall temperature and stress of the T4 tank when the T2 tank fired or the T1 and T2 tanks fired simultaneously in the absence of wind were discussed. The specific layout is shown in Figure 1. The tank is a large internal floating roof tank with a volume of 10000m$^3$, a diameter of 28m, a wall height of 17.85m, a top height of 3058mm and a distance between the two storage tanks of 40m. T1 and T2 store gasoline with a filling factor of 0.85, a density of 750kg/m$^3$, a burning rate of 0.0225kg/(m$^2$·s), and a combustion heat of $4.4 \times 10^4$kJ/kg; the T4 tank is an empty tank.

![Figure 1. Partial layout of the T-1](image)

3. Heat radiation intensity distribution of adjacent tanks
Based on the data obtained by the large-scale (15m diameter) pool fire test conducted by the research group using No. 180 fuel oil, the theoretical calculation value and the test measurement value were compared. Select the flame height model and thermal radiation calculation model that are more suitable for large hydrocarbon fires.

3.1. Selection of flame height model
Thomas formula and Heskestad equation are widely used in the calculation model of pool fire flame height [7-8]. Compare the average flame height measured in the test with the theoretical flame height calculated by Thomas formula and Heskestad equation, as shown in Figure 2.

![Figure 2. Comparison of flame height for experiments and theory](image)

Through the above comparison, Thomas formula is more accurate for the estimation of flame height, so in the following related calculation, Thomas formula is used to calculate the flame height. The Thomas model has the following expressions in the absence of wind and wind [7]:

\[ \frac{H}{D} = 42 \left( \frac{m''}{\rho_0 \sqrt{gD}} \right)^{0.61} \quad \text{(windless)} \]  
\[ \frac{H}{D} = 55 \left( \frac{m''}{\rho_0 \sqrt{gD}} \right)^{0.67} (u^*)^{-0.21} \quad \text{(wind)} \]

Where \( H \) is the visible height of the flame, m; \( D \) is the diameter of the liquid pool, m; \( m \) is the air density, kg/m\(^3\); \( g \) is the acceleration of gravity, 9.8 m/s\(^2\); \( m'' \) is the mass combustion rate of the unit pool area, kg/(m\(^2\)·s); \( \rho_0 \) is the vapor density of flammable liquid, kg/m\(^3\).

3.2. Selection of radiation mode

At present, the point source model and the solid flame radiation model are mostly used to calculate the thermal radiation under pool fire [9-10]. Point source model and solid flame radiation model are used to calculate the theoretical value of thermal radiation corresponding to each test, as shown in Figure 3-2.

From Figure 3, it can be seen that the solid flame radiation model is more similar to the test value, while the point source model is quite different, especially in the case of test 3. According to Code for design of oil depots (GB50074-2014) [11], the distance between tanks shall not be less than 0.4D, and if D = 15 m, the minimum distance shall be 6 m. The error of the solid flame radiation model at 6 m is less than 6.5%, which is less than the test result and within the acceptable range, while the error of the point source model in test 3 is as high as 19.7%. To sum up, the accuracy of the solid flame radiation model is higher, and the solid flame radiation model is widely used to calculate the heat radiation of large hydrocarbon fires [9].

![Figure 3. Comparison of the calculated results and experimental measurements of the radiant flux from the pool fire](image-url)

The solid flame model assumes that the flame is a cylinder with a diameter and a length equal to the pool diameter and the length of the visible flame plume. The expression is as follows [9]:
\[ I = E'F\tau \]  

(3)

Where: \( E' \) is the average radiation intensity of the flame surface, kW/m\(^2\); \( F \) is the geometric view factor; \( \tau \) is the atmospheric transmittance.

When the total radiant energy radiates uniformly outwards from the side and the top of the cylindrical flame, the expression of \( E' \) is as follows [12-14]:

\[ E' = \frac{0.25\pi D^2\eta m''\Delta H_c}{0.25\pi D^2 + \pi DH} \]  

(4)

Where: \( \eta \) is the efficiency factor, which is taken as 0.13-0.35; \( \Delta H_c \) is the combustion heat of liquid, kJ/kg;

### 3.3. Calculation of heat radiation distribution of adjacent tanks

Mainly study the effect of T4 (empty tank) on the heat radiation of adjacent storage tanks. The tank wall of T4 tank is divided into 36 surfaces (one surface every 10 degrees) and the adjacent flame (in case of fire, the temperature of the tank wall near the fire source of the adjacent tank changes greatly), the left and right symmetrical 16 surfaces and the top of the tank are selected as the objects. The thermal radiation value of T4 storage tank is shown in Table 1.

| Cases          | Symmetry plane | Heat radiation/ KW·m\(^{-2}\) |
|----------------|----------------|--------------------------------|
| T2 Fire        | left/right     | 19.32 16.51 12.99 10.53 8.23 6.52 5.63 4.87 4.23 |
| T1 and T2 Fire | left           | 28.52 27.77 25.82 21.79 17.43 14.53 12.50 9.76 6.35 |
|                | right          | 27.33 23.38 19.67 15.42 11.86 9.23 7.97 6.41     |

### 4. Thermal response analysis of adjacent tanks based on ANSYS

In this section, ANSYS Workbench environment is used to simulate the wall temperature and corresponding stress of adjacent tanks under the influence of single heat radiation and heat radiation coupling.

#### 4.1. Tank model construction

1. Basic assumption
   - In the case of fire, the mechanism by which adjacent storage tanks are affected is complex. Both the tank wall and the tank top are affected by the heat radiation, and the convective heat transfer between the heated tank and the air [15]. For simple calculation, the following assumptions are made:
     - 1) The tank is made of Q235B steel, and the thickness of tank wall is equal to 12mm (take the average thickness);
     - 2) Neglecting the heat transfer through the welding seam;
     - 3) Assuming that the wind speed has no effect on the transfer of heat radiation;
     - 4) Assuming that the convection coefficient is not affected by temperature.

2. Establishment of geometric model
   - The Design Modeler (DM) module in Workbench is used to build the geometric model of inner floating roof tank, as shown in Figure 4.

#### 4.2. Thermal response process simulation

Import the geometric model into the Transient Thermal module to define the parameters of the tank wall; use the adaptive grid method to divide the grid and select a grid with a size of 0.5m (the grid density is Medium and the smoothness is High, Transition is Slow), you can get a smooth and high-quality grid. The mesh division is shown in Figure 5, which divides 59215 nodes and 163117 units.
Apply the heat radiation value obtained in Section 3.2 to the corresponding surface (a total of 16 surfaces) and tank roof, and set the thermal boundary conditions of the storage tank model. Set the initial ambient temperature to 22 °C. The convection coefficient of the tank wall and air is set to 5 W/(m²·°C), and the radiative emissivity is set to 0.28 [16].

Based on the study of time to failure [17], this paper sets three response times of 600s, 1200s and 1800s to solve. Import the temperature distribution into the Transient Structural module to solve the corresponding equivalent stress.

4.3. Temperature field adjacent to tank
Figure 6 and Figure 7 show the temperature response of the adjacent tank wall under the influence of single heat radiation and heat radiation-heat radiation coupling. It can be seen that under the influence of a single heat radiation, the wall temperature of the tank is generally symmetrical with the wall closest to the fire source, and the highest temperature appears on the wall closest to the fire source, and the highest temperatures of the three response times are 348.72°C, 584.17°C, and 781.55°C; when affected by the coupling effect of heat radiation-heat radiation, the temperature is no longer symmetrically distributed due to the different distances between the tank wall and the two fire sources, the highest temperature appears on the wall surface receiving the largest stack heat radiation, the highest temperature of the three response times are 435.58°C, 709.8°C and 957.79°C, respectively. At the same time, under the same condition, the temperature of each wall is higher than that of single heat radiation.
Figure 7. Temperature fields of tank wall under thermal radiation coupled effect

Figure 8. The curve of maximum temperature under different working conditions

Figure 8 shows that the temperature of tank wall rises rapidly in the thermal response stage. With the increase of temperature, the radiation energy of the tank wall increases gradually, and the rising speed of temperature slows down.

Import the temperature distribution into the Transient Structural analysis module to solve the corresponding equivalent stress. The solution shows that at three response time points, the maximum equivalent stress (Von-Mises) of the storage tank under single heat radiation and multi-heat radiation coupling effects are 26.77Mpa, 62.36Mpa, 113.5Mpa and 33.4Mpa, 78.95Mpa 144.7Mpa.

4.4. The analysis of adjacent tanks time to failure

Relevant research shows that there are two cases of tank wall stress failure and medium combustion in the tank under the influence of heating radiation [15]. This paper only studies the tank wall stress. The European Steel Construction Association (ECCS) analyzed the influence of temperature on materials through a large number of experiments, and fitted out the relationship between steel yield strength and temperature [15]:

\[
\frac{\sigma_s^T}{\sigma_s^{20}} = 1 + \frac{T}{767 \ln \left( \frac{T}{1750} \right)} \quad 0 \leq T \leq 600^\circ C
\]

(5)

\[
\frac{\sigma_s^T}{\sigma_s^{20}} = 108 \frac{1 - T/1000}{T - 440} \quad T > 600^\circ C
\]

(6)
Where: $\sigma_{s20}^{0}$ and $\sigma_{sT}^{0}$ are the yield strength of the steel at 20 °C and T °C respectively. According to the above relationship, the curve of yield strength of Q235B steel varying with temperature is shown in Figure 9.

According to the above relationship, the curve of yield strength of Q235B steel varying with temperature is shown in Figure 9.

![Figure 9. Comparison of equivalent stress and yield strength](image)

Figure 9. Comparison of equivalent stress and yield strength

As The highest equivalent stress of the three response time points simulated is converted into the relationship between equivalent stress and temperature, compared with the yield strength change curve, as shown in Figure 9, where equivalent stress 1 is the tank wall stress under the influence of single heat radiation, and equivalent stress 2 is the tank wall stress under the influence of coupled heat radiation. It can be seen that when the tank wall temperature reaches about 600 °C, the equivalent stress is greater than the yield strength of the material, and the material fails. Comparing the failure temperature with figure 8, it is obtained that when the tank is affected by a single heat radiation, the time to failure is about 22 minutes, and when the heat radiation-heat radiation coupling effect is affected, the time to failure is about 15 minutes.

5. Conclusion and further work
(1) Comparing the experimental data with theoretical calculations, it is concluded that the calculation models of flame height and heat radiation which are more suitable for large-scale hydrocarbon fires are Thomas formula and solid flame radiation model, respectively.

(2) The temperature distribution and the corresponding stress of the adjacent tank were obtained with ANSYS-Workbench software under the influence of single heat radiation and multi-thermal radiation.

(3) The results show that the time to failure of the tank is about 22 minutes when it is affected by the single heat radiation, and the time to failure of the tank is about 15 minutes when it is affected by the coupling effect of heat radiation-heat radiation.

Based on the study of this paper, considering the additional safety barriers, it is the future research direction to establish the domino effect expansion probability model of tank accidents.

Acknowledgments
The authors thank the financial support of the National Natural Science Foundation of China (71971110) and 2017 Six talent peaks project in Jiangsu Province and National Key R&D Program of China (No. 2016YFC0800100).

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