Influence of thermal stratification by fire on heat-mass coupling response mechanism of the liquefied tank

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Abstract: In order to study the explosion-inducing process and thermal response of fire-induced BLEVE (boiling liquid expanding vapor explosion), a small experimental device was established. The radiant heating source was used to simulate the external fire heat effect, and superheated water was used as the medium. The pneumatic ball valve was used to simulate the leakage action. The gas-liquid flow, internal pressure and temperature transient response of the tank during the heating and venting processes were measured, and the superheated process of the medium in the tank was analyzed. The temperature-pressure coupling response after the explosion was traced to investigate the thermal action of the fire on the tank. The experiment found that the heating of the storage tank was the generation and gradual disappearance of temperature stratification. The crack action would result in the breaking of phase equilibrium and pressure rebound. There was an overheat delay in the detonation, and the temperature stratification would prolong the overheat time of the medium. There was a lower limit for the occurrence of the BLEVE accident, the critical stratification degree was used to quantify the limit and the limit of this experimental condition was $\xi \leq 2.33$.

1. Introduction

Liquid gas is a conventional fuel for industrial production and usually stored in the liquid storage tank area. These tanks would be a source of danger when a fire breaks out. The tanks of carrying liquid gas, which are close to the fire area, will be directly attacked by heat radiation and weaken the tank wall. Simultaneously, liquid gas, heated and pressurized in the tank, caused ruptures and other accidents, such as boiling liquid expansion vapor explosion (BLEVE) seriously. The most serious incident was a leaking liquefied petroleum gas (LPG) pipeline caught fire and explosion in Mexico City in 1984. The explosion killed 650 people and injured more than 7,000 people[1]. Behrouz Hemmatian's research works found the fire is the most common cause of accidents through an analysis of 202 BLEVE accidents in recent years[2]. Many scholars have done a lot of research on this[3-5].

K. Moodie observed that five cylindrical propane storage tanks were heated in a pool fire for 30 minutes. He found that there was a temperature difference between the gas and liquid phases by a record of the medium temperature changing[6]. Birk carried out many multi-group LPG storage tank experiments in a pool fire. It was found that thermal stratification was related to liquid energy through the analysis of liquid pressure and gas-phase temperature. Ultimately, the energy determines the boiling and the pressure rebound[7]. Lin, Gong Yanwu explored the process of heating liquid gas.
storage tanks comparing the heating belt and water. They found that liquid thermal stratification determined the storage tank’s internal pressure, and the degree of delamination was affected by heat flux and filling\[8\]. F. Heymes conducted a remote fire experiment that adopted liquid gas wall combustion on the sidewall. He studied the impact of different heating levels on the pressure and temperature inside the tank by changing the flame intensity and distance\[9\]. Birk conducted a pool fire study on multiple groups of propane tanks. The pressure relief valve (PRV) was set to open at 1.9 MPa in this experiment to record the pressure and temperature of the storage tank after leakage. The effect of different release pressure of PRV on the BLEVE process was quantified\[10\]. The above studies had explored the thermal stratification phenomenon of storage tanks and their influencing factors under fire conditions. However, they lack an in-depth analysis of the heating stage of the storage tank. Moreover, the coupled response of thermal and medium is split after the explosion release.

Therefore, based on the small scale experimental equipment for radiant heating of the sidewall, this paper researched the thermal response of the storage tank under the action of the external radiant heat of 60 kW/m². We focused on the temperature-pressure change during the heating process and analyzed the influence of different initial conditions, as well as after the explosion release.

2. Experimental device and procedure
The device, which equipped the thermal radiation invasion tank, was showing in figure 1. The radiant heating source was used to simulate the thermal action process, which applied external flame radiation to the tank. The radiant heating source (1 m×1 m) was composed of 12 equidistant silicon carbon rod arrays, which generated 0--100 kW/m² stable radiant heat flux through power control. This device was a cylindrical stainless steel high-pressure storage tank (14 L, Φ = 180 mm, h = 772 mm, ranging from 0-20 bar). It was equipped with a magnetic level gauge in the outer wall used to control the level of the liquid. The pressure and temperature were recorded by sensors inside the tank. A high-frequency pressure transmitter P1 (HM90, ranging from 0~20 bar (0.25%)), was arranged on the top of the container. Additionally, the experiments designed 6 K type thermocouple T1-T6 (0.5 mm), which distributed in \(\phi_h = 90\%, 70\%, 50\%, 30\%, 10\%\) and 5% level. Midi Logger GL980 was used to collect temperature and pressure data in the experiment.

![Figure 1](image)

Figure 1 (a) Schematic of the experimental setup for the radiant heating source to the tank and (b) temperature distribution with the time and position.

In order to ensure repeatability and safety of the research experiment, the test medium was replaced by superheated water and pneumatic ball valve (d = 20 mm) simulated tank rupture. In order to eliminate the impact of air on the water-steam system in the tank, the device was equipped with a vacuum pump. The tank will be vacuumsed before the experiment, then the radiant heating source would be turned on. When the specified heating power would be set to heat the tank, the recorder would be opened to collect data with a frequency of 1 Hz. However, data collection and preservation should be stopped when the over-hot water state was about to reach the termination condition. Then, we changed the acquisition frequency to 1000Hz, immediately opened the valve, and recorded the temperature, pressure and other parameters in the tank.

Aim to clarify the stratification effect of different temperatures of the storage tank, this experiment
selected 70% charging degree and 60 kW/m² heat flux radiation to heat the liquid phase of the storage tank. We took the medium T6 temperature as the termination temperature. In the experiment, 7 groups of temperatures, including 60 °C, 65 °C, 70 °C, 75 °C, 80 °C, 90 °C and 100 °C, were selected as the termination temperature. When the medium reached the termination temperature, the valve was opened. The experiment was repeated 3 times in each condition to reduce the influence of the heating processes and experimental measurement errors.

3. Results and discussions

3.1. Thermal response of the medium during the heating

Figure 2 showed the transient of radiant heat fluxes at the experimental terminal temperature of 60 °C, 80 °C, and 100 °C, respectively. These three sets of experiments were spent 53 min, 70 min, and 93 min, respectively. The results showed that the curves of radiant heat flux coincide well under different conditions, and the radiant heat flux remains relatively stable after reaching 60 kW/m² for 45±1 min.

![Figure 2 Transient of radiant heat fluxes at the experimental terminal temperature of 60 °C, 80 °C and 100 °C](image)

Figure 2 Transient of radiant heat fluxes at the experimental terminal temperature of 60 °C, 80 °C and 100 °C

Figure 3(a-c) showed the response process of the medium temperature inside the tank at the terminal temperatures of 60 °C, 80 °C and 100 °C. The heating of the tank wall increases the temperature of the fluid, and the density of fluid closing to the tank wall decreases by the radiant heating source. Thus the natural convection is formed in fluid, so that heat transfer of the flow layer was continuously accumulated at the surface and inside of the liquid. Then the liquid temperature gradually increases in the horizontal and vertical directions. The temperature stratification (20 min) was produced in the liquid phase temperature due to the influence of thermal buoyancy. With the accumulation of the radiative heat transfer, a vanishing point of stratified temperature appeared at the temperature of 80 °C for 66 min (figure 3(b)). The liquid temperature T2 was equal to T3 in the point, which meant the temperature stratification disappeared above the location of T3 of the storage tank. The second peak appeared at 83 min in figure 3(c), indicating that the liquid phase temperature had stratified from top to bottom disappeared layer by layer. However, there was no stratified vanishing point occurring at the 60°C all along (figure 3(a)). In addition, the surged temperature occurred before the disappearance of the three temperature stratification points, which further explained that the thermal conductivity of the upper high-temperature flow layer was the main reason for the disappearance of the liquid phase temperature gradient.

Due to the unilateral heating of the radiant heating source and the effect of the flowing boundary layer, the liquid temperature of the tank was presented in wedge-shaped temperature distribution. The temperature distribution on the tank’s longitudinal section was shown in figure 1(b). With the accumulated heat flux, temperature stratification of the tank became a generation to gradual disappearance and the temperature stratified level moved down gradually. The liquid phase region was uniform which above the temperature stratified interface at 69 min, and the temperature stratification level gradually moved downward as the heating progress.
3.2. The coupled response of heat-mass during detonation

Besides, the coupling response law of pressure (P1) and temperature (T2-T6), were further studied at 90 °C termination, as shown in figure 4(a) and (b). The supercooled region was below the saturation pressure-temperature curve, and above the curve was the superheated region. Point A-H were eight characteristic points that describe the whole blowout process. Point A, B, and C correspond to the pressure-temperature point at the time of pre-blowout pressure, minimum pressure and peak pressure respectively, while point D-H were the characteristic point at the same time interval after the peak pressure.

It could be seen that point A was in the state of supercooling before the explosion in figure 4(b), indicating that the medium was in gas-liquid equilibrium at this time. Rarefaction wave was produced by the explosion location to the tank internal transmission, resulting in the broken of the gas-liquid phase balance. Then the medium was overheated instantaneously and boiled conditions. Liquid medium at position T2 lasted 3 s in a state of overheating and returned to a cold state (D-H). Therefore, the medium went through a process that supercooled--superheating--supercooled. It was worthy that the overheating interval of the liquid phase at the T4 location was 8.8 s. The only explanation was temperature stratification that causing longer overheat latency below the T4 position. Meanwhile, the boiling happened from top to bottom, the superheated layer of the medium would continue to flow upward with the gas-liquid flow during the boiling process. Therefore, the T4 temperature measurement point would continuously monitor the superheated state of the medium. Since there was no obvious difference in the temperature between T2 and T3, the overheating delay of the liquid was extremely small.

In addition, the experiment showed that the liquid phase at the positions of T5 and T6 was always in the supercooled region, and the liquid phase of the lower position was in a larger temperature stratification. When the upper liquid was rapidly overheated and boiled, the lower subcooled liquid was not yet overheated and boiled. Then the lower medium began to overheat and boil, the upper gas-liquid flow filled with high temperature. For one thing, the lower medium’s overheat was suppressed, resulting in the lower liquid always in the state of supercooling. For another, it would be mixed with the supercooled liquid resulting in its temperature rise.

Figure 4(a) Pressure response and (b) pressure-temperature curve at termination temperature of 90 °C
3.3. Analysis of critical conditions for BLEVE occurrence

In order to obtain the critical conditions for BLEVE, three points of ABC (figure 5) were plotted on the saturation pressure-temperature curve in the above conditions. For 70 °C-100 °C conditions, point A was in the supercooled region and points of BC were in the superheat region. While points A, B, and C were in the supercooled region for 60 °C and 65 °C conditions. It was obvious that the temperature condition less than 65 °C will never occur in the BLEVE. For further exploring the heated tank pressure rebound of the critical condition after the explosion, the temperature 65 °C of stratified factor \( \xi \) was approximately judged as pressure rebound after the explosion:

\[
\xi \leq \xi_{cr}, \text{BLEVE happen}
\]  

\( \xi \) is the stratified factor (1)

In this paper, the stratification of critical criterion\(^{[11]}\) is defined as follows:

\[
\xi = \frac{P}{P_{sat}}
\]

Where: \( P \)--actual pressure in the tank, bar; \( P_{sat} \)--saturation pressure corresponding to the average temperature of the medium in the tank, bar;

According to the study of 60 kW/m\(^2\) radiant heat flux and 70% tank liquid level, data analysis was conducted for 7 experimental conditions (termination temperature of tank T6 temperature reached 60 °C-100 °C respectively). The average temperature in the tank was interpolated by MATLAB software. The average temperature of 7 working conditions was 87.70 °C, 95.61 °C, 105.88 °C, 116.35 °C, 126.52 °C, 144.87 °C, and 164.55 °C. Therefore, the tank internal medium degree of stratification was 2.63, 2.33, 2.16, 1.93, 1.85, 1.50, 1.49 by Stratification formula (2). Thus, this paper preliminarily infers that \( \xi > 2.33 \) was a critical criterion that BLEVE accidents would not occur.

4. Conclusions

(1) When the tank was heated by heat radiation, the temperature stratification would be formed from top to bottom and gradually disappear. And there was a temperature surge before the emergence of the temperature stratification vanishing point.

(2) A certain overheating delay in the process of BLEVE under the existence of temperature stratification would result in the prolonged overheating time of the medium. At the same time, the temperature difference of the liquid pushed the uniform temperature distribution of the whole liquid, and reduced the risk of the overheated boiling to impact the gap.

(3) The critical criterion \( \xi_{cr} \) could judge BLEVE accidents of the tank, which are caused by external heat. It was inferred that the occurrence of BLEVE was \( \xi \leq 2.33 \) in this experiment. This paper believed that the criterion \( \xi_{cr} \) would have important guiding significance for the prevention and rescue of BLEVE accidents.

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