Thermal Response and Safety Analysis of the Liquefied Gas Storage Tank at Low Filling Ratios

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ABSTRACT

Experimental and numerical research was conducted to investigate the effect of liquid filling ratios on the thermal response and safety of a vertical cylindrical liquefied gas storage tank. Low filling ratios were considered to reveal the distribution characters of the medium temperature and wall temperature, as well as the pressure rise histories. The results show that with less liquid filled, the dry wall temperature was higher thus lead to the wet wall to be hotter and more heat transferred into the liquid medium from per unit wall area. As a result, the temperature in the bulk liquid zone rose faster and the stratification degree was larger and last longer. Under the combined influence of the higher pressure and the degradation of the wall material at the higher temperature, the less filled tank can stand for shorter period in thermal environment. Moreover, if the tank failed after the same heating period, the high grade energy retained in the liquid medium under lower filling ratio would more likely bring serious consequence.

KEYWORDS: Liquefied gas, storage tank, filling ratio, thermal response, safety analysis.

INTRODUCTION

As a clean energy carrier and fuel, hydrogen has been widely used in chemical industry, mechanical treatment, transportation and so on. With the increasing of hydrogen consumption, it can be argued that we are entering the hydrogen economy era in some sense [1]. But, because the density and saturated vapor pressure of hydrogen are very low, its storage becomes a major issue in the utilization process [2]. Among the storage technologies, cryogenic and compressed hydrogen are more common on the client side for ease of use [3]. And the storage tanks for hydrogen are always affected by the thermal environments, such as solar radiation and even fires happened for various reasons [4, 5].

Some researchers conducted experimental and numerical researches about the thermal response of the hydrogen storage tanks that were subjected to external fires [6-8]. They proposed that heat transfer performance of the tank depended on both the fire impingement and the internal medium [6]. The mechanical properties of the tank materials could degrade under high temperature [7]. And in some cases, the tank might burst without the activation of pressure relief device [8]. Once the tank spilled or the pressure relief device activated, the rapidly ejecting hydrogen would mix with air immediately and reach the flammable range. As the tank wall was very hot, the flammable mixture would be easily ignited [9], and sometimes even self-ignited without any external ignition source due to high rupture pressure [10, 11]. Under these circumstances, explosion accidents will be unavoidable, which is not desirable especially in the hydrogen fueling stations [12]. So far,

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however, specific regulations have not fully established in such application areas [13] and thorough analysis and intensive research works still need to be done about the safety of hydrogen storage.

The response of the medium and tank wall of liquefied hydrogen storage tanks under heat impingement, which is similar with the compressed hydrogen storage tank at the dry wall and vapor phase region and involved coupled heat and mass transfer process of the two-phase system, was focused on in this paper. On this question, the physical essences of the liquefied hydrogen, liquefied petroleum gas and liquefied natural gas tanks are identical. Therefore, we can analyze this problem from a more basic and extensive perspective. It is already a consensus that the tanks loading liquefied gases which heated by the external environment are quite likely to be thermal stratified. Numerous studies demonstrated that thermal stratifications have a direct effect on the pressure rising and medium energy storage in the liquefied gas storage tanks [14-16].

During the formation of stratification, liquid close to the hot wall continues to float up and accumulate at the top of the liquid surface. This leads the pressure in the tank, which is determined by the temperature of the liquid surface, rising more quickly when the liquid is stratified than that without stratifications. Meanwhile, with the surface temperature same as that of the non-stratified liquid, the energy storage in the stratified liquid is much less, because when there are thermal stratifications, the liquid under the surface was subcooled and thus the average temperature of the liquid is lower than that of the uniform one.

Researchers have pointed out that the less liquid energy can reduce the risk of boiling liquid expanding vapor explosion (BLEVE) of liquefied gas tanks [17-18]. Birk and Cunningham [17] analyzed the effects of the flame form and the pressure relief valve (PRV) action on the liquid temperature stratification, and that of the temperature stratification on the BLEVE hazards. They pointed out that if the tank was fully filled with liquid, and the liquid temperature was uniformly equal to the saturation temperature corresponding to the PRV opening pressure, the resulting BLEVE will be most powerful. Lin [18] had carried out a series of tests related to the stratification of LPGs in the tank heated by the outer heating. They drew from the experimental results that the higher the filling ratio was, the smaller the degree of the liquid stratification would be and the LPG with a uniform temperature might cause high pressure recovery and increase the probability of the occurrence of BLEVE.

The existence of the stratifications inner the tanks will also affect the temperature rising of the tank wall [19]. And the temperature distribution in the tank wall will directly affect the failure mode of the tank and the severity of the accidents [20]. Different conditions like fire scenarios, filling ratios will all influence the response and consequently the failure of the tank [21]. So analyzing the response of a liquefied gas tank should consider the coupled process of the heat and mass transfer inner the tank and that across the tank wall. In our previous works [22-26], the basic physical process of the thermal response of the liquefied gas storage tank and the effect of fire engulfment on that were experimentally and numerically researched. The research objective of this paper is to experimentally and numerically investigate the thermal response and analysis the safety of the liquefied gas storage tank at low filling ratios, which is usually considered less dangerous. Thermal response characteristics such as medium temperatures, wall temperatures and tank pressures of the liquefied gas storage tank under two different low filling ratios were detailed analyzed to reveal the specific phenomena in these cases.

RESEARCH METHODS

As shown in Fig. 1, the experiments were carried out on a vertical cylindrical tank, the diameter and the height of which are 325mm and 835mm respectively, and the tank was made of pressure vessel steel Q345R (Chinese National Standard GB-713) with the wall thickness of 8mm. The testing tank was heated outside on the vertical wall by electric heater, and the low liquid filling ratios of 40% and 50% were investigated. The pressure inner the tank and temperatures of the liquid and vapor phases were monitored in the tests. There were five temperature sensors set at equal longitudinal intervals in the tank. And the pressure sensor was protected by using circulating cooling water to avoid the high temperature effects. In order to ensure safety, water was used instead of liquefied gas in these experiments. To ensure consistency of the physical problem, the air in the tank was excluded before experiments.

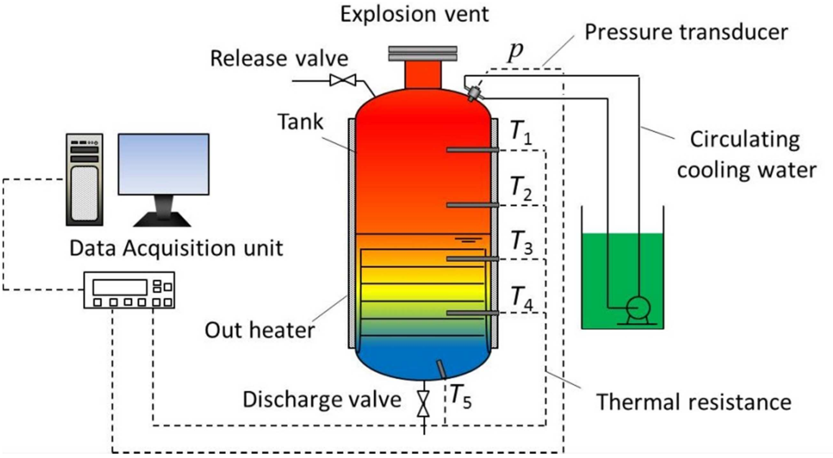

Fig. 1. Schematic diagram of the experimental apparatus.

The numerical research of the coupled heat and mass transfer in the multi-zone and multi-phase field was conducted based on the calculation model developed in our previous work [24]. As shown in Fig. 2, the multidimensional heat conduction process in the solid zone as well as the stratified flow, interphase mass transfer, and multi-mechanism heat transfer in the liquid-vapor two-phase system were simultaneously solved, so as to reflect the integrated response features under the effect of the different filling ratios. The simulations were implemented on the platform of ANSYS fluent 12.0 and the calculating conditions were listed in Table1.

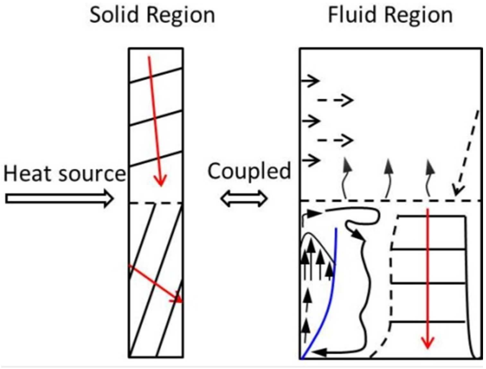

Fig. 2. The simulation model.

Table 1. The calculation conditions

Filling ratio	Heating power	Initial thermal state	Initial temperature
40%/50%	5kW	Vapor-liquid equilibrium	Uniform (314K)

RESULTS AND DISCUSSIONS

This section presents the experimental temperature histories under the different filling conditions, and the detailed thermal response predicted by simulations.

Thermal responses of the medium

Figure 3 shows the generating and disappearing processes of the thermal stratifications under the 40% and 50% filled conditions. In the two conditions, the monitoring points T1 and T2 were both located in the vapor region and the points T3-T5 located in the liquid region, while the liquid level was just above T3 for the former (40%) and between T2 and T3 for the latter (50%). And Ts represented the saturation temperature corresponding to the tank pressure. Taking the 50% filled situation for example, the temperature curves reflect that the vapor phase and the liquid phase experienced two different response modes. For the vapor phase, the temperature was uniform (saturated with the tank pressure) at first and stratified (overheated with the tank pressure) as the heating went on. For the liquid phase, the temperature was stratified once heated and gradually became uniform after a certain amount of time.

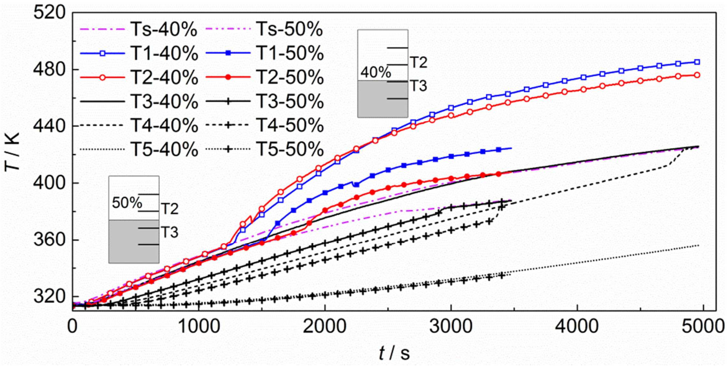

Fig. 3. Temperature responses of the medium under 40% and 50% filling rates.

Comparing the results of the two tests, it can be found that under the 40% filled condition, the overheating of the vapor phase was earlier (1250 vs 1540 s) while the beginning of the de-stratification (3425 vs 2595 s) and the entirely eliminated time of the stratification (5000 vs 3500 s) in the liquid phase were later than the 50% filled condition. It indicated that the filling ratio of the liquid in the tank had a significant influence on the thermal response of the medium, and consequently on that of the solid wall and the safety of the whole tank.

Thermal responses of the tank wall

Numerical simulations of the above testing conditions were conducted for detailed analysis of the response of the tank under different filling ratios. Figure 4 shows the simulated wall temperature distributions at 2500 s. As can be seen, the temperature of the wall close to the vapor phase was much higher than that close to the liquid phase (the initial liquid levels were located at 0.195 m and 0.255 m respectively in the two tests) and presented peak values around the height of 0.35 m under 40% filling ratio and 0.42 m under 50% filling ratio. In addition, the wall temperature was overall higher at the 40% filled condition and the high temperature area in the vapor phase wall was larger at the 40% filled condition.

Figure 5 shows the variation trend of the wall temperature distributions in the de-stratification stage (after 2595s) of the heating process under 50% filled condition. Seen from the figure, as the elimination of the thermal stratification in the liquid phase, the temperature distributions in the vapor phase wall varied little but overall increased greatly, while that in the liquid phase changed obviously with that in the de-stratification region basically keeping stable and that in the stratification region rose significantly.

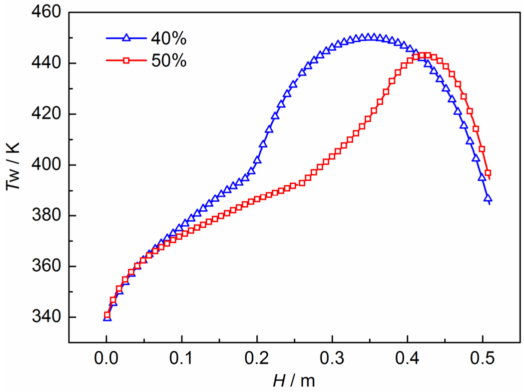

Fig. 4. The simulated wall temperature distributions at 2500 s.

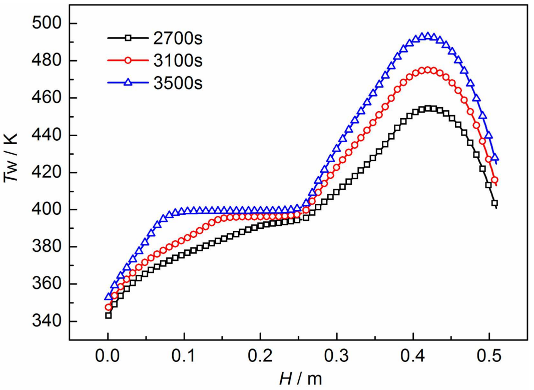

Fig. 5. Wall temperature distributions during de-stratifying under 50% filling ratio.

Figure 6 shows the comparison of the wall temperature distributions under the two filling conditions in de-stratifications stage. The difference in the temperature distributions of the vapor phase wall was similar to that in the stratification stage shown in Fig.4. But the temperature of the liquid phase wall under the 40% filling condition was no longer totally higher than that under the 50% filling condition due to the faster de-stratification in the latter case. Above results proof that under the coupled heat transfer mechanism, the different filling ratios of liquefied gas in the storage tank not only dominated the evolution process of the medium thermal stratification, but also affected the thermal response of the tank wall.

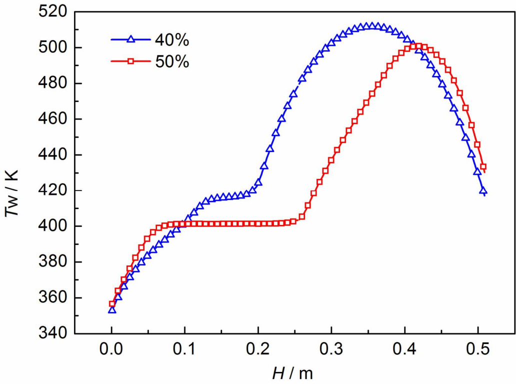

Fig. 6. Comparison of the wall temperature distributions at 3700 s.

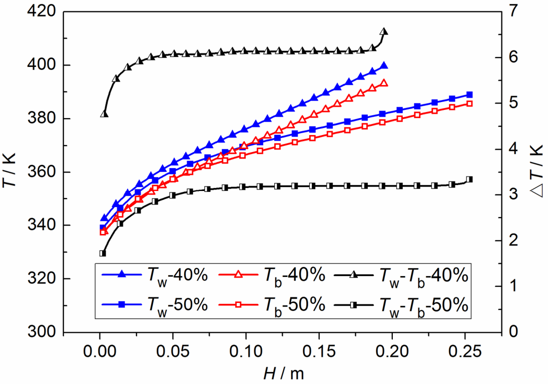

Fig. 7. The temperature difference under different filing conditions.

Detailed effect of the filling ratios on heat transfer process

Under the low filling ratio conditions, the area of the dry wall which next to the vapor phase medium, was larger and consequently the temperature in this region was higher owing to the low heat capacity of the vapor medium. Affected by the hotter dry wall, the temperature in the wet wall, which next to the liquid phase medium, was also higher under the lower filling ratio condition, according to the analysis in the previous section. To further reveal the effect of the liquid filling ratio on the medium responses, the temperature differences between the hot wall (T_w) and the adherent fluid (T_b), as well as that between the boundary fluid (T_b)and the bulk fluid (T) in stable stratification stage (1300s) were drawn in Fig.7 and Fig.8 respectively.

Figure 7 shows that the temperature different between the inner liquid wall and the adherent liquid under 40% filling ratio was much higher than that under 50% filling ratio. It means there was more heat transferred to the medium from per unit area of the hot wall. As a result, the liquid temperature, especially the liquid surface temperature which controls the tank pressure, would rise more quickly under this condition.

Figure 8 shows that the temperature difference between the boundary layer and the bulk liquid presented the same tendency under the two liquid filling ratio conditions. Unlike the temperature difference between the tank wall and the adherent liquid, the temperature difference inside the medium was lower under the lower filled condition this time. It suggested that when the filling ratio was lower, the accelerating rising of the bulk liquid temperature was more significant relative to that of the liquid in the boundary layer. In other words, the increased heat transfer rate from the hot wall to the medium had actually enhanced the energy accumulation in the bulk liquid.

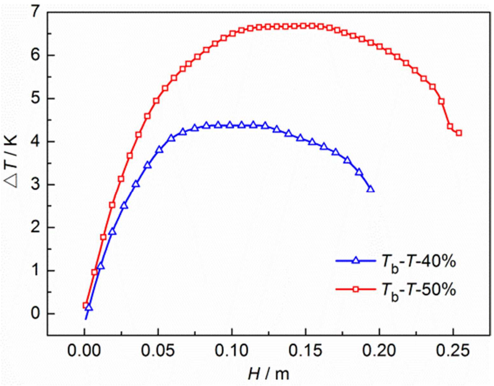

Fig. 8. The temperature difference between the boundary layer and liquid bulk.

Safety analysis of the liquefied gas storage tank under different filling ratios

The heating were proceeded till the stratifications in the liquid bulk was entirely eliminated, which were at 5000 s and 3500 s respectively for 40% and 50% filled conditions. In order to make a complete comparison, the heating was kept for the same duration. Figure 9 shows the simulated pressure histories under the two conditions. As can be seen, the pressure rising rate were both decreased as the disappearance of stratifications under the two conditions, and the pressure under the 40% filling ratio rose faster in the whole course of stratification and de-stratification. According to the above analysis, the maximum wall temperature was located at the vapor phase wall and that under the 40% filling ratio was always higher than that under the 50% filled condition. These results mean that the storage tank with less liquefied gas filled was more prone to failure under the combine impact of high pressure and wall material degradation due to the high temperature.

Figure 10 presents the simulated temperature distributions of the liquid medium along the axis under the two test conditions. It can be seen that the temperature value and gradient were all greater in the 40% filled condition. Under such circumstances, if the tank failed under the similar pressure (implied that the liquid surface temperature was about the same), the total energy would be larger in the higher filled condition owing to small temperature gradient and more quantity of medium, which may lead to the happening of explosive boiling and furtherly boiling liquid expanding vapor explosion (BLEVE). Otherwise, if the tank failed after the same heating period for other reason such as mechanical impact, although the mass of the medium was greater, a high energy retained in the liquid medium under lower filling ratio would more likely to cause serious consequences.

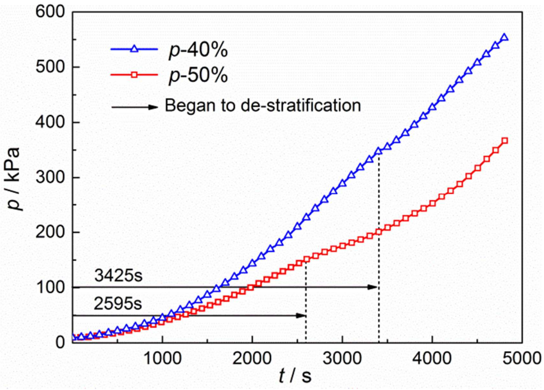

Fig. 9. The pressure responses under different filing ratios.

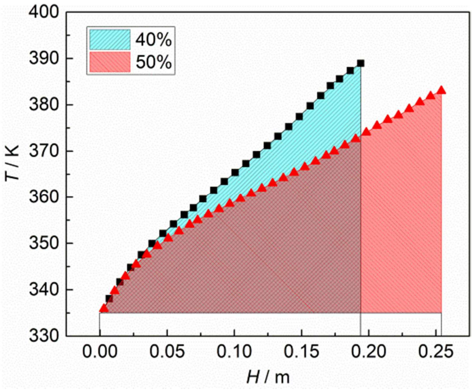

Fig. 10. Liquid temperature distributions along the axis.

CONCLUSIONS

Effect of liquid filling ratios on the thermal response and safety of a vertical cylindrical liquefied gas storage tank under low filling ratios was investigated by experiments and calculations. Comparative analyzis of the distribution characteristics of the medium temperature, wall temperature at the stratification and de-stratification stages, as well as the pressure rising histories lead to the following conclusions:

(1) Under the lower filling ratio, the maximum wall temperature was higher, and high temperature area in the vapor phase wall was larger. As a result, both the liquid wall temperature and the temperature difference between the liquid wall and the medium were higher. This increased the growth rate of the temperature in the bulk liquid zone, as well as the degree and duration of stratification.

(2) Corresponding to the rapid rising of liquid temperature, the pressure rising rate was also faster under the lower filling ratio. Meanwhile, because of the degradation of the wall material at high temperature, the tank can stand for shorter period in thermal environment.

(3) If the tank failed under the similar pressure, the higher filling pressure is more dangerous, and it may cause the boiling liquid expanding vapor explosion (BLEVE). Otherwise, if the tank failed after the same heating period for mechanical impact, the high grade energy retained in the liquid medium under lower filling ratio is more likely to cause a serious consequence.

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