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Effect of fire engulfment on thermal response of LPG tanks

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ABSTRACT

A model has been developed to predict the thermal response of liquefied-pressure gases (LPG) tanks under fire, and three-dimensional numerical simulations were carried out on a horizontal LPG tank which was 60% filled. Comparison between numerical predictions and published experimental data shows close agreement. The attention is focused on the influence of different fire conditions (different fire scenarios, various engulfing degrees and flame temperatures) on thermal response of LPG tanks. Potential hazard probabilities under different fire conditions were discussed by analyzing the maximum wall temperature and media energy after the internal pressure rose to the same value. It is found that the less severe fire scenario and lower engulfing case may lead to a greater probability of burst hazard because of the higher maximum wall temperature and media energy before the pressure relief valve (PRV) opens.

1. Introduction

High-temperature environment outside the liquefied-pressure gases (LPG) tank can cause tank explosion due to pressure rise inside the tank and strength drop of the tank wall. When heated by fires engulfing the tank, the liquid space would be thermal stratified, and the tank pressure would climb rapidly because it was determined by the upper warmer liquid [1]. Meanwhile, the material strength of tank wall would drop a lot as the wall temperature went up significantly [2]. These are the two essential causes of LPG tank explosions.

The thermal response of LPG tanks under jet fire and pool fire has to be researched to prevent LPG tank explosions. Birk and Cunningham [3] have conducted a series of experiments on the propane tanks subjected to fire. They investigated the influence of fire engulfment on the time for destratification of the liquid. Birk and his group [4] have also researched the failure of tanks under partially engulfing fires, and found that the worse fire condition did not necessarily result in the worse rupture outcome thanks to the earlier pressure relief valve (PRV) activation. Landuccia et al. [5] suggested that the introduction of fire protection coatings may be an effective measure to improve the safety of LPG tanks through pool fire engulfment tests on LPG tanks. Xing et al. [6–10] have implemented experiments of 35.5 L tanks under jet fire and pool fire respectively, and carried out numerical simulations on thermal response of LPG tanks by FLUENT. They have summarized the factors affecting the thermal response of LPG tanks engulfed by fire, namely size of the tank, filled level, fire condition, relief valve and so on. Li and others [11] have carried out numerical simulations on the heat radiation process of pool fire, and analyzed the distribution of heat flux around the flames. In general, the related works are mostly a number of researches on the specific conditions. In order to obtain a general rule, it may be a primary problem to investigate that how fire conditions affect the thermal response of LPG tanks. And different fire conditions can be simulated more conveniently by numerical approach than conducting numerous experiments. There have been some computational codes developed to model full and partial fire engulfment of LPG tanks in open literatures [12,13]. However, the analysis of different fire engulfment needs to be improved.

In this paper, a three-dimensional numerical model for LPG tanks involved in fire engulfment was set up, and the thermal responses of an LPG tank in different fire conditions were simulated to analyze the effect of fire engulfment.

2. Simulation models

2.1. Mathematical model

The present model is available for the thermal response processes of LPG tanks engulfed in fires before the PRV opens. Once flames act on the tank, liquid adjacent to the heated wall will be hotter and lighter, and then the lighter liquid will go up to the surface according to the mechanics of natural convection, which will cause thermal stratification in the tank. As previously mentioned, the pressure of vapor space is mainly determined by the upper warmer liquid and there is no pressure relief before the PRV opens, for this reason the thermal state of liquid is more likely to

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Table 1
Characteristics of HSE test.

Item	Specification
Tank length (mm)	3276
Tank diameter (mm)	1200
Tank wall thickness (mm)	7.1
Tank material density (kg/m^3)	7818
Tank material specific heat (J/(kg K))	502.4
Tank material thermal conductivity (W/(m K))	54.26
Internal medium	Propane
Initial temperature (K)	293
Liquid volume fraction (%)	60
PRV opening pressure (MPa)	1.81

be saturated for the upper layer and super cooled for lower layers. So the gasification mode is assumed to be evaporation.

The numerical simulations were performed on the computational fluid dynamics (CFD) software FLUENT by solving volume fraction equation, momentum equations, energy equation and turbulent equations. Pressure-based solver was selected considering the relatively lower flow speed in this case and implicit time integration was adopted. Volume of fluid (VOF) model was chosen to solve the multiple phase problems and renormalization group (RNG) k–ε model was used to deal with turbulence. The volume fraction equation of the liquid phase was discretized in modified version of the High Resolution Interface Capturing (HRIC) scheme [14] while momentum and energy equations in second order upwind scheme and turbulent equations in first order scheme. The face values of pressure involved in the discretization form of momentum equations were computed by the body-force-weighted method. Densities were supposed relating to both temperature and pressure for vapor and only varying with temperature for liquid, and the first-order upwind scheme was chosen to identify the density values at cell faces.

2.2. Simulation object

The simulation object is a horizontal LPG tank which was used in the fire experiment by British Health & Safety Executive (HSE) in 1995 [15]. The characteristics of HSE test are listed in Table 1.

2.3. Mesh generation

A three-dimensional geometric model of the horizontal cylindrical tank was set up and gridded by GAMBIT. The geometry was divided into solid zone (refer to the tank wall) and fluid zone (the inner space). Hexahedral meshes were generated for the cylinder part of the fluid region and the solid region; unstructured tetrahedral meshes were used for the ellipsoid head space of the vessel. The volume mesh of the tank is shown in Fig. 1.

2.4. Thermal boundary conditions

Heat transfer from the flames to the tank wall is a mixed effect of convection and radiation: mixed model was enabled for wall region engulfed by fire while convection model for free wall region. In case of pool fires, the heat flux is generally 70–100 kW/m^2, which is equivalent to 700–800 °C of flame temperature. The heat transfer coefficient of engulfed region was calculated as follow [16]:

$$h_c = 4.6 \times 5.678 \left(\frac{2.338}{D}\right)^{0.195} \quad (1)$$

where h_c, D are the heat transfer coefficient (W/(m^2 K)) and tank diameter (m). In case of jet fires, flames produce fiercer heating effect (the heat flux can exceed 200 kW/m^2 [17]) than pool fires, and the equivalent heat transfer coefficient is referred from [18].

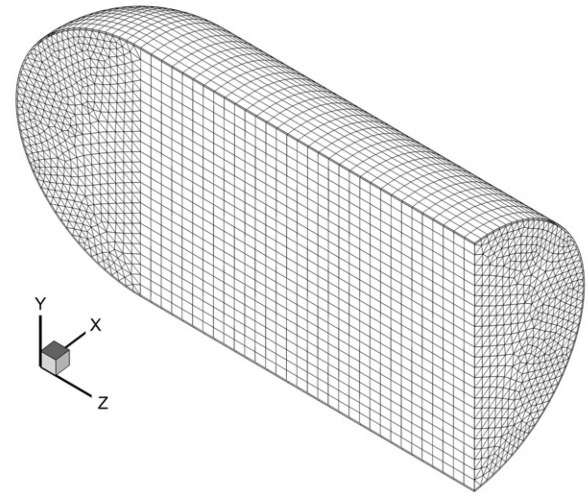

Fig. 1. Volume mesh.

Heat transfer coefficients for vapor and liquid space are different due to the different value of thermal conduction and heat capacity. Moreover, these parameters are temperature-dependent, and the flow velocities are transient. So the heat transfer coefficients between tank wall and media are also changing with time.

The tank was subjected to fires simultaneously in vapor space and liquid space, while the engulfment of fire only differs in horizontal direction. Different degrees of fire engulfment were addressed by setting different wall regions. Figs. 2 and 3 show the 50% and 25% engulfment in which red spaces (dark gray spaces in the printed version) stand for the heated walls.

3. Results and discussion

3.1. Validation

In the experiment of HSE [15], PRV opened at about 110 s. Correspondingly, the comparisons of calculation results with experimental data from initial state to 110 s are given in Figs. 4 and 5. The figures show that the calculated pressure and wall temperatures are in good consistency with the experimental ones.

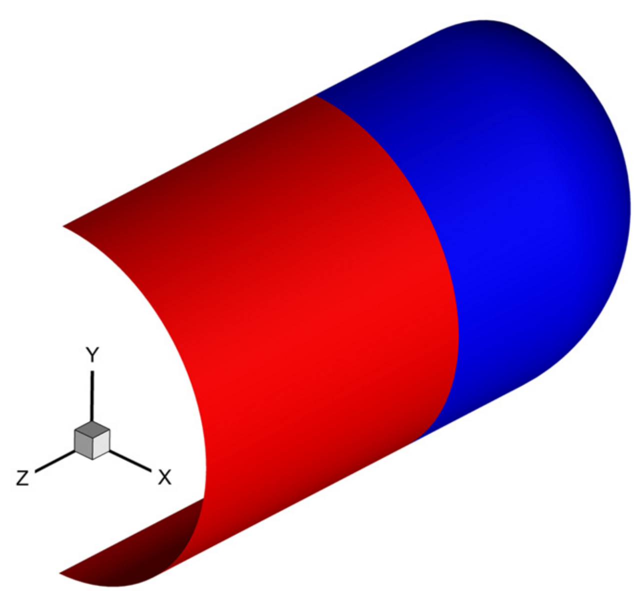

Fig. 2. 50% fire engulfment.

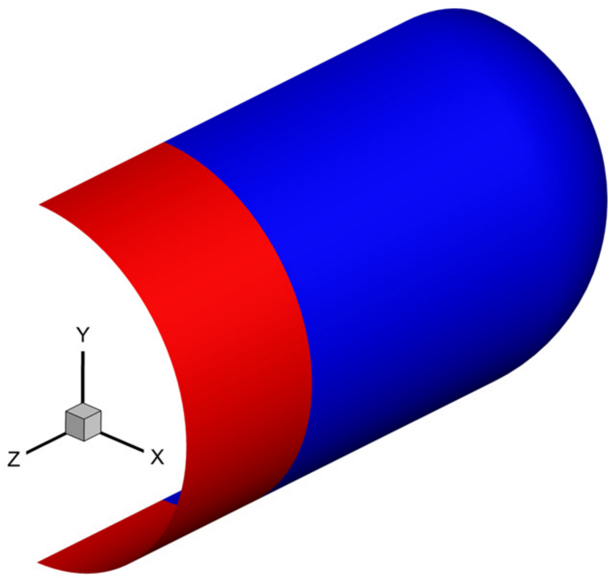

Fig. 3. 25% fire engulfment.

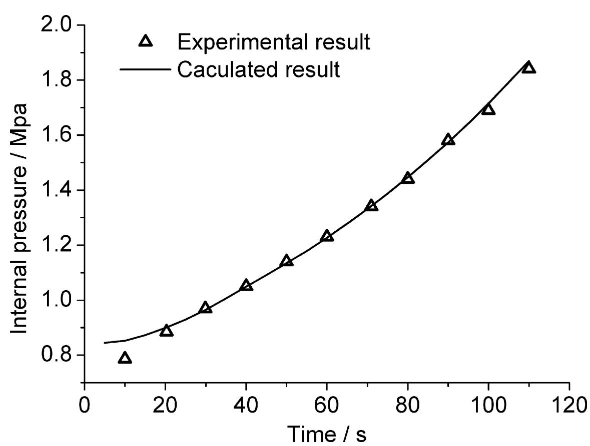

Fig. 4. Response of internal pressure.

Take 110 s for example, the measured pressure was about 1.84 MPa, while the calculated one is 1.87 MPa at the moment; the calculated temperatures are 30 K and 40 K higher than the measured ones for vapor wall and liquid wall, respectively; and the calculation errors

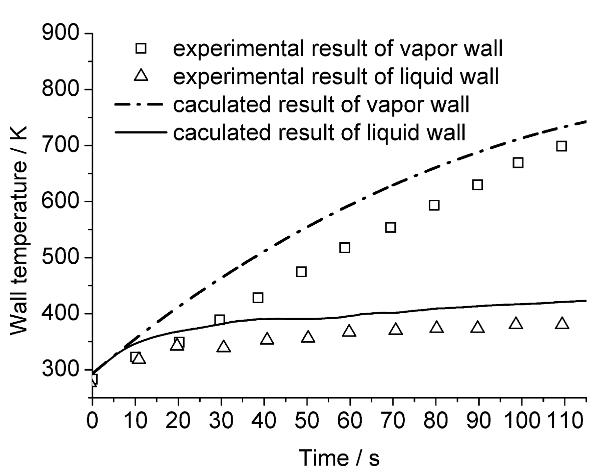

Fig. 5. Response of wall temperature.

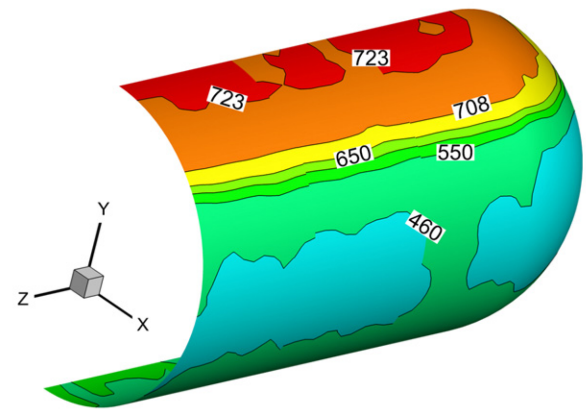

Fig. 6. Distribution of wall temperature at 110 s (all numerical values are in K).

are 1.6%, 4.3% and 10% separately for internal pressure, vapor and liquid temperature. It is thus evident that the model this paper developed is valid to predict the thermal responses of LPG tanks under the fire engulfment before PRV opening.

Fig. 6 shows the distribution of wall temperature in 110 s when all engulfed in jet fire. It is obvious that the wall temperature is higher in the vapor space and the maximum takes place at the top of the tank. The reason is that liquid has a more remarkable cooling effect on hot wall than vapor because of its larger heat transfer coefficient, and the heated gas rose constantly to the upper part.

Fig. 7 shows the media temperature contours in 110 s under full fire engulfment of jet fire. We can see that the temperature is higher at the top and lower at the bottom with obvious thermal stratification.

3.2. Effect of different fire scenario

The response processes of LPG tank subjected to jet fire and pool fire before PRV acting (namely the internal pressure came to the set value of 1.87 MPa) are given in Figs. 8–11. It can be seen from Fig. 8 that the pressure rose slowly in pool fire and got to 1.87 MPa at 415 s (which is 110 s in jet fire). Figs. 9–11 show the curves of maximum wall temperature, vapor temperature and liquid temperature in jet fire (0–110 s) and pool fire (0–415 s), respectively. The vapor temperature is taken 10 cm below the top of the tank, and the liquid temperature is taken 10 cm above the bottom of the tank (the media temperatures are taken in the same way in the following sections). The figures show that the maximum wall temperature reached 870 K in the case of pool fire which is higher than that of jet fire (734 K), and the media temperatures rose to 482 K and 401 K separately for vapor and liquid in pool fire, both higher than that in jet fire (356 K and 326 K).

The results indicate that the less severe fire condition (here refers to pool fire relative to jet fire) can lead to a greater probability of burst hazard because of the higher wall temperature when the tank was heated to the equal internal pressure, somewhat similar to the conclusion proposed in [4] through field experiments. Moreover, both vapor and liquid had a higher energy in pool fire than in jet fire when the internal pressure climbed to the same value which means higher degree of superheat once the PRV opened and can cause more serious recapture of pressure.

3.3. Effect of fire engulfing degree

The effect of fire engulfing degree on thermal response of LPG tanks in jet fire was investigated. Three different degrees of 25%, 50% and 100% were examined. The results are shown in Figs. 12–15. It can be seen from Fig. 12 that the rate of internal pressure rise

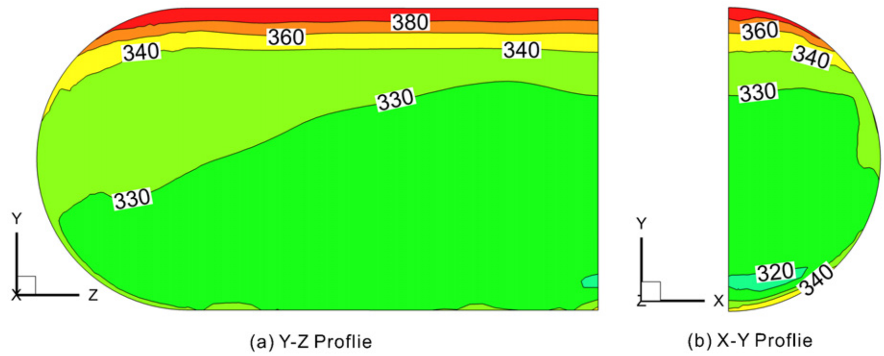

Fig. 7. Contours of media temperature at 110 s (all numerical values are in K).

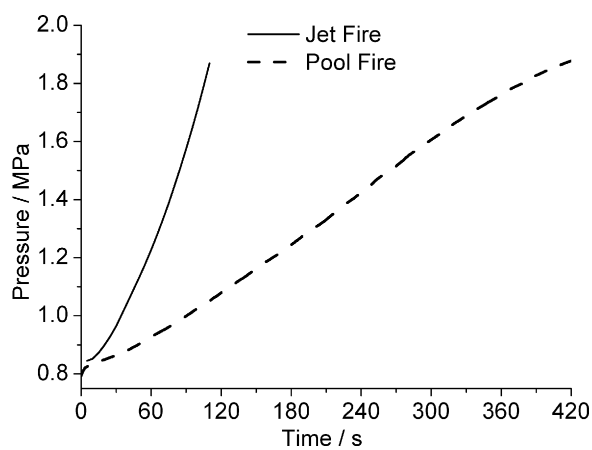

Fig. 8. Responses of pressure in jet fire and pool fire.

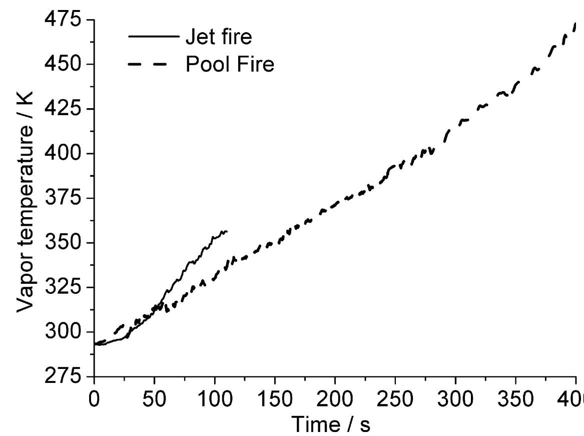

Fig. 10. Responses of vapor temperature in jet fire and pool fire.

increases with the fire engulfment: the pressures have reached the set value of 1.87 MPa at 110 s, 195 s and 390 s for 100%, 50% and 25% engulfed jet fire, respectively.

Fig. 13 shows that the maximum wall temperatures under different fire engulfment differ a little, and we can conclude that fire engulfing degree almost has no effect on the maximum wall temperature. So, the maximum wall temperature at the moment just before the PRV acting would be higher in less engulfed case, because of the longer period for internal pressure getting to the set value.

Figs. 14 and 15 show that the rates of media temperature rise increase with the fire engulfment. It can be found in Figs. 14 and 15 that the vapor temperature separately reached 356 K in 110 s, 367 K in 195 s and 368 K in 390 s for 100%, 50% and 25% engulfment of jet fire, and the liquid temperature got to 322 K in 110 s, 327 K in 195 s and 328 K in 390 s for 100%, 50% and 25% engulfment of jet fire.

It can be summarized from the results that the lower engulfing degree of fire environment makes slower rises of pressure and media temperatures, while the rising rate of maximum wall temperature is unaffected. As a result, more time is needed for the internal pressure to reach the same value, and so the maximum wall temperature will be greater then. Also, both the temperatures of vapor and liquid will be slightly higher at that time. In a word, for fire of the same feature (refers to fire scenario and flame temperature), the lower engulfing degree may cause more dangerous consequence.

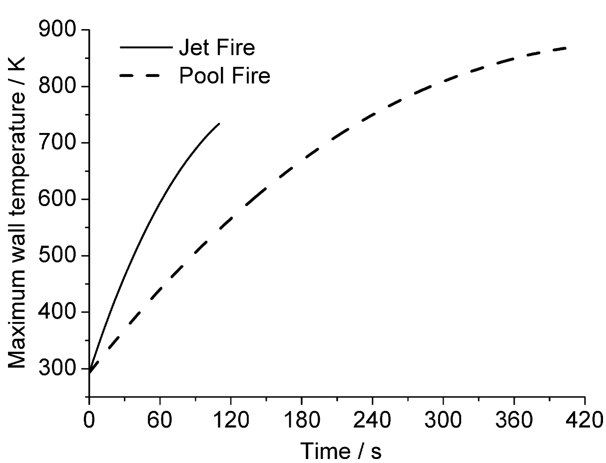

Fig. 9. Response of maximum wall temperature in jet fire and pool fire.

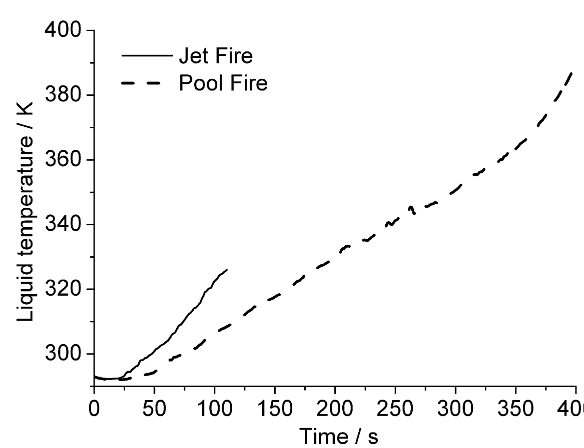

Fig. 11. Responses of liquid temperature in jet fire and pool fire.

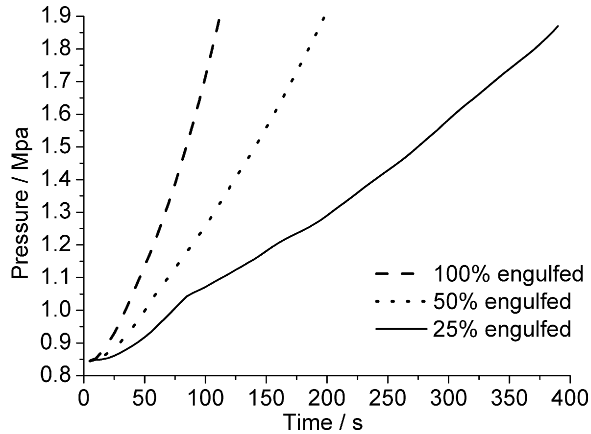

Fig. 12. Responses of pressure in different engulfment of jet fire.

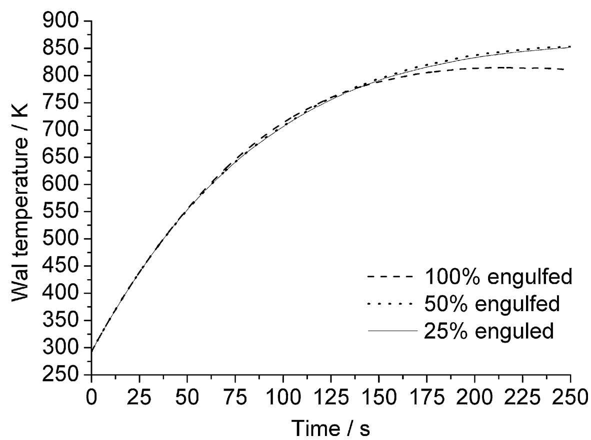

Fig. 13. Responses of maximum wall temperature in different engulfment of jet fire.

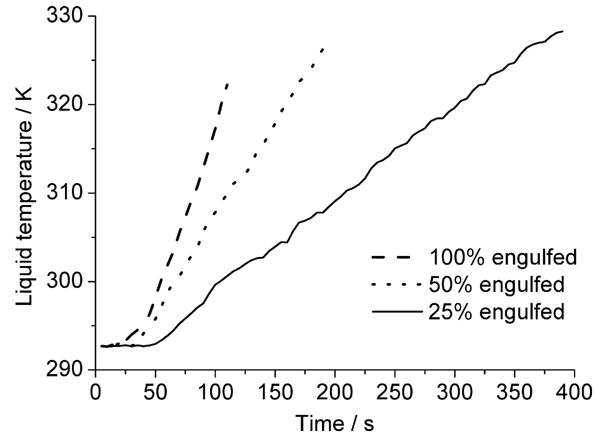

Fig. 15. Responses of liquid temperature in different engulfment of jet fire.

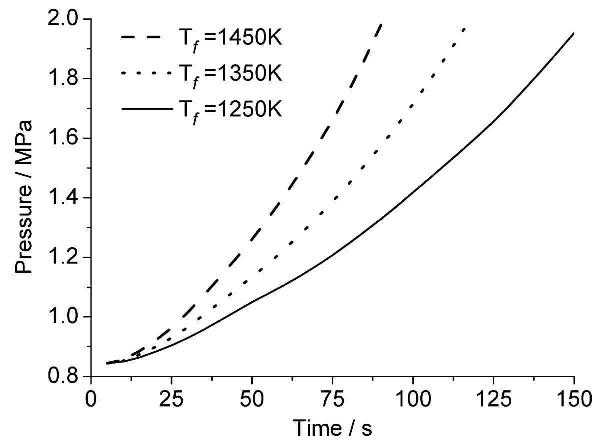

Fig. 16. Pressure trends under different flam temperatures.

3.4. Effect of flame temperature

The heat dissipating, as well as the air–fuel ratio which results in different combustion reaction rates and further in different heat generations, may affect by the wind direction and speed. This may finally cause differences in flame temperature. In the case of full fire engulfment, simulations under different flame temperatures T_f in jet fire were conducted. Figs. 16–19 display the trend lines of pressure and temperature according to heating time. Fig. 16 shows that internal pressure reached 1.87 MPa at about 85 s, 110 s and 145 s for different T_f value of 1450 K, 1350 K and 1250 K, respectively. The time periods of 85 s, 110 s and 145 s are adopt in discussing the effect of different flame temperatures on the responses of wall temperature and media temperatures below. It can be seen from Fig. 17 that the maximum wall temperature increased more rapidly when the flame temperature is higher: the maximum wall temperatures separately reached 792 K in 85 s, 734 K in 110 s, 670 K in 145 s for 1450 K, 1350 K and 1250 K jet fires. Figs. 18 and 19 show that the rate of vapor temperature increase with time were greater than that of liquid temperature: the vapor temperatures are 359 K at 85 s, 356 K at 110 s and 350 K at 145 s for 1450 K, 1350 K and 1250 K

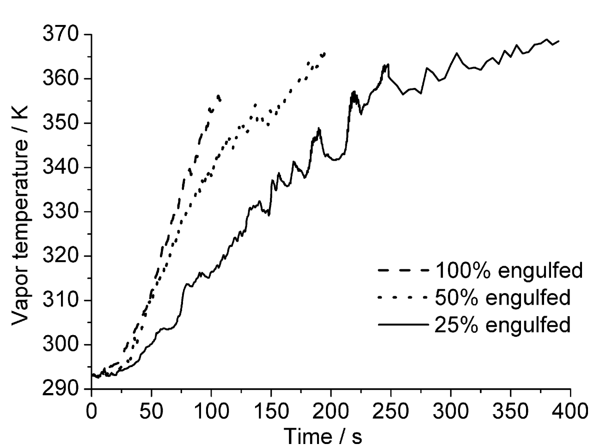

Fig. 14. Responses of vapor temperature in different engulfment of jet fire.

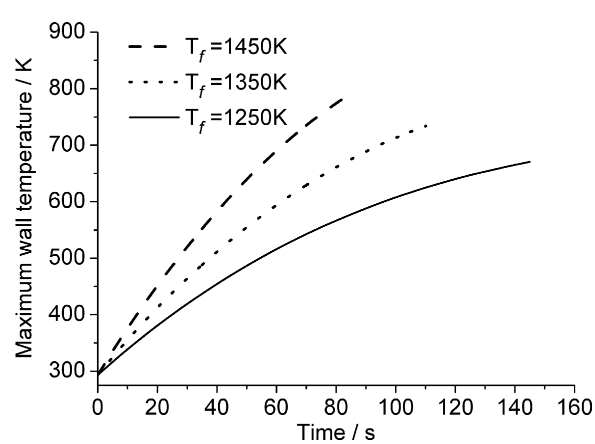

Fig. 17. Maximum wall temperature trends under different flam temperatures.

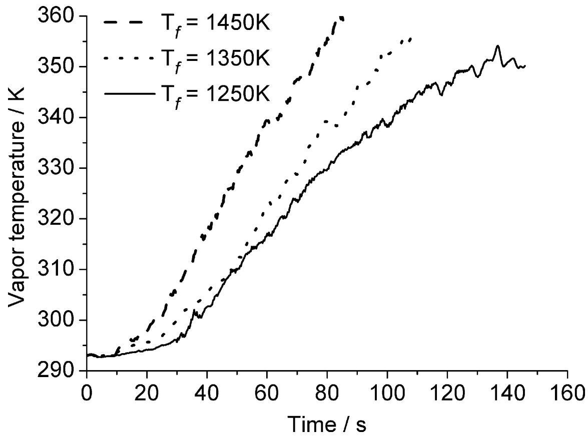

Fig. 18. Vapor temperature trends under different flam temperatures.

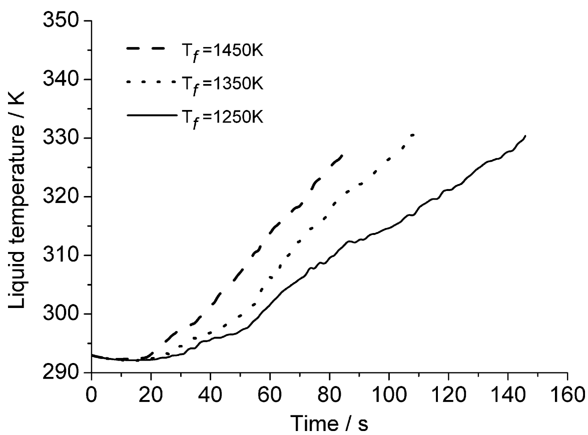

Fig. 19. Liquid temperature trends under different flam temperatures.

jet fires; the liquid temperatures are 328 K at 85 s, 332 K at 110 s and 330 K at 145 s for 1450 K, 1350 K and 1250 K jet fires.

Then, it is clear that at the moment when internal pressure rises to the set value, the maximum wall temperature of the tank is lower under the lower temperature flames, but the vapor temperatures and liquid temperatures are similar when the tank is subjected to different temperature flames, meaning that the energy of media is generally equal. Conclusion can be drawn that lower flame temperature of the same fire mechanism brings a lower risk of tank failure after the same pressure is reached.

4. Conclusion

A series of three-dimensional numerical simulations were carried out on the model of the LPG tank that British HSE used in experiment [15] by means of FLUENT software. Thermal response processes of the LPG tank under different fire conditions were investigated concerning different fire scenarios, various engulfing degrees and flame temperatures. The calculation results described the rising trends of internal pressure, maximum wall temperature and media temperatures through which we can predict the security of LPG tanks. The following comments itemize the main conclusions:

(i) Under pool fire, compared with jet fire, the internal pressure and temperatures increase more slowly. As a result, it takes a longer period to reach the same pressure. When PRV opens, both vapor and liquid are of higher energy which means greater degree of superheat and can cause more serious recapture of pressure after rapid relief. Meanwhile the maximum tank wall temperature is higher. Thus the less severe fire scenario can be more dangerous.

(ii) The rising rates of pressure and media temperatures both increase with the fire engulfing degree, but the rising rate of maximum wall temperature is free from it. So in lower engulfing degree case, the maximum wall temperature will be greater and the media energy will be higher when the internal pressure goes up to the value that will open the PRV. That means the fire of lower engulfing degree can cause more serious consequence if using the same pressure relief program.

(iii) Lower flame temperature brings slower pressure and temperature rises. When the same pressure is reached, the wall temperature is lower and the energy of media is generally equal. Conclusion can be drawn that under the fire with lower flame temperature of the same mechanism and engulfing degree, the LPG tank is at the less risk of explosion.

Acknowledgements

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