

Short communication

A simplified model to predict the thermal response of PLG and its influence on BLEVE

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Abstract

A simplified model has been developed to describe the thermal response of pressure liquefied gas (PLG) tanks subjected to fire. The development of the stratification layer is considered in this model. Comparison of results with available experimental data shows that our proposed model can reasonably predict the thermal response. The effect of stratification on the liquid energy is also summarized. Results show that the pressure in the tank rises faster as a result of thermal stratification, and for the same tank pressure the energy in the liquid is less when the liquid is stratified. Stratification can reduce the severity of hazards of boiling liquid expanding vapor explosion (BLEVE). © 2004 Elsevier B.V. All rights reserved.

Keywords: PLG; BLEVE; Stratification; Liquid energy; Fire engulfment

1. Introduction

The boiling liquid expanding vapor explosions (BLEVEs) that were discussed by Reid in 1979 [1] are known for their unexpectedly severe consequences. In most cases, BLEVEs come into being in the following sequence: (a) a pressurized liquefied gas (PLG, such as LPG (liquefied petroleum gas)) leaks and is lit by fire, (b) a PLG tank is exposed to high temperature fire resulting tank weakening, (c) a crack is caused by the internal pressure; the internal pressure drops abruptly, and (d) the tank ruptures with sudden depressurization, and the violent boiling of superheated PLG.

During the process of a BLEVE, the tank fails because of increasing internal pressure and high wall temperature and from the violent pressure rebound after sudden depressurization, bubble formation, and choked flow develops. A more energetic response results from a higher loading temperature. So a BLEVE is severely affected by the mass and the temperature of the loading. Many researchers have studied the mechanism of BLEVE [2–11].

Most work has focused on small- and moderate-scale experiments [3–5] and some correlations were developed. Unfortunately, these correlations only apply for the reported test conditions.

Some models were also utilized to predict the thermal response of LPG. Chen and Lin [6] had presented thermal response models for worst-case scenarios of a horizontal ammonia tank with complete fire engulfment. Ciambelli et al. [7] modeled the internal tank pressure of a tank truck transporting LPG in a highway tunnel when a BLEVE occurred. Their models supposed that the system was divided into several zones with homogeneous node temperature. Prugh [8] calculated the energy based on the uniform temperature. However, it has been proven that liquid temperature stratification affects the pressure in the tank and the pressure recovery upon depressurization [9]. When fire engulfs the PLG tank, the liquid near the wall is heated and becomes less dense and rises to the top. The tank pressure is dictated by the temperature of the top liquid, which means that the pressure in the tank is higher than that calculated from the average liquid temperature. When depressurization happens, the liquid energy in the tank will be less than that calculated from the average liquid temperature.

The field modeling approach and zone modeling techniques were used in [10,11] to simulate the thermal

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Nomenclature

A	heat transfer area (m^2)
c	specific heat capacity ($\text{kJ kg}^{-1} \text{K}^{-1}$)
E	energy (W)
g	gravitational force (N)
Gr	Grashof number
h	height (m)
k	specific heat ratio
m	constant
n	constant
P	pressure (Pa)
Pr	Prandtl number
q	heat flux (Wm^{-2})
R	radius of tank (m)
t	time (s)
T	temperature (K)
u	velocity (ms^{-1})
U	characteristic velocity of the boundary layer
V	volume (m^3)
W	equivalent of TNT (kg)
x, y	coordinate systems
Z	vertical distance from the bottom of stratification layer (m)

Greek letters

β	coefficient of thermal expansion (K^{-1})
δ	boundary layer thickness (m)
θ	temperature difference (K)
ν	kinematic viscosity ($\text{m}^2 \text{s}^{-1}$)
ρ	density (kg m^{-3})
τ	shear stress at the wall (Nm^{-2})

Subscripts

atm	atmosphere
b	boiling
B	bulk
L	liquid
p	pressure
s	stratification layer
V	vapor
w	wall
x	distance between the bottom of the tank and the stratification layer

stratification of the LPG tank. Although the model can accurately predict the tank pressure, its complexity makes it difficult to use in many situations.

In contrast to the previous investigations, the present paper proposes a simple model for predicting the thermal stratification of PLG. The effect of thermal stratification on BLEVE is also discussed. Approximate solutions are then compared with available experimental data.

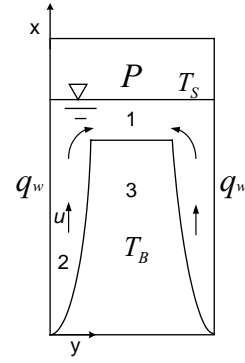


Fig. 1. The sketch map of the stratification model.

2. Thermal model

It is necessary to first calculate the liquid temperature. The tank in the stratification model is vertical and cylindrical. The content is divided into a vapor zone and a liquid zone. As shown in Fig. 1, the liquid zone is composed of three zones: the stratification layer, zone 1; the boundary layer, zone 2; the bulk, zone 3. Their temperatures are T_s , $T(x)$ and T_B , respectively. Warm liquid comes into the stratification layer through natural convection of the boundary layer and the bulk temperature remains unchanged $T_B = T_0$. That leads to the development of a thermal stratification layer whose temperature is higher than that of the bulk, i.e. $T_s > T_B$.

Simplifying assumptions used in the derivations are as follows:

- the initial temperature of the liquid and vapor is T_0 ;
- the heat flux q_w through the wall is uniform;
- the vapor and liquid are always in equilibrium;
- the Boussinesq approximate is appropriate;
- the boundary layer starts at the bottom of the tank and the natural convection is turbulent.

Thus, the velocity profile and temperature profile for the turbulent free convection boundary layer can be respectively written as:

$$\frac{u}{U} = \left(\frac{y}{\delta}\right)^{1/7} \left(1 - \frac{y}{\delta}\right)^4 \quad (1)$$

$$\frac{\theta}{\theta_w} = 1 - \left(\frac{y}{\delta}\right)^{1/7} \quad (2)$$

where u is the local velocity in the boundary layer (m s^{-1}); U the characteristic velocity of the boundary layer (m s^{-1}); δ the boundary layer thickness (m); $\theta = T - T_B$ the temperature difference in the boundary layer (K); $\theta_w = T_w - T_B$ the increase in wall temperature over that of the bulk liquid (K).

The integral energy and momentum equations for the boundary layer can be respectively expressed in the following way:

$$\frac{d}{dx} \left[\rho \int_0^\delta (R - y) u^2 dy \right] = \rho \beta g \int_0^\delta (R - y) \theta dy - \tau_w R \quad (3)$$

$$\frac{d}{dx} \left[\rho c \int_0^\delta \theta(R-y)u \, dy \right] = Rq_w \quad (4)$$

where the shear stress at the wall, τ_w , and the temperature difference θ_w can be respectively obtained as suggested by Yang and Pu [12]:

$$\tau_w = 0.0225 \rho U^2 \left(\frac{U\delta}{\nu} \right)^{-1/4} \quad (5)$$

$$\theta_w = 44.44 \frac{q_w}{\rho c U} \left(\frac{U\delta}{\nu} \right)^{-1/4} Pr^{-2/3} \quad (6)$$

Then, substituting Eqs. (1)–(4) into Eqs. (5) and (6), assuming that a power law variation for $\delta (=a_1 x^{n_1})$ and $U (=a_2 x^{n_2})$ in the form, and considering that the order of the magnitude of δ is less than that of R , n_1 , n_2 , a_1 , a_2 can be determined by a similar method as that of Yu et al. [13], i.e. $n_1 = 5/7$; $n_2 = 3/7$; $a_1 = [10^5 R^4 (6.95 Pr^{-7} + 3.1 Pr^{-19/3}) / Gr_R^*]^{1/14}$; $a_2 = 0.1424 \nu / (Pr^{\delta/3} a_1^5)$, where $Gr_R^* = \beta g q_w R^4 / k \nu^2$.

Since the boundary layer is known, the variation of the stratification layer with time can also be known. The time Δt for adding an incremental volume ΔV into the stratification layer is:

$$\Delta t = \frac{\Delta V}{\left(\int_0^\delta u \, dA \right)_x} \quad (7)$$

As suggested by Gursu et al. [14], the temperature distribution in the stratification layer is assumed as $E(Z) = mZ^n$, where m and n are constants, $E(Z)$ the temperature rise in the stratification layer, Z the vertical distance from the bottom of the stratification layer (m).

Then we obtain the following:

$$E(Z) = \frac{q_w A t (n+1)}{\pi R^2 \rho c} \frac{Z^n}{\delta_s^{n+1}} \quad (8)$$

The warmest liquid dictates that the pressure in the tank can be assumed. With this pressure known, the vapor mass can be determined. This calculated new mass is then compared with the vapor mass of the previous step. If the new mass is larger, then the liquid vaporization is required. The liquid mass after evaporation can be determined by iterative calculation based on the fact that the increased sum of the vapor enthalpy and the liquid enthalpy equals to the heat quantity transferred into the tank.

3. Liquid energy

From the discussion above, we can know that the temperature of PLG is one of the most important factors that influence BLEVE.

The analysis of the experiments in [4] showed that the liquid energy affecting the development of the crack during BLEVE could be described as:

$$E_L = f \left(\frac{T_{\text{sat}}(P) - T_{\text{SL}}}{T_{\text{SL}}}, V_L \right) \quad (9)$$

where T_{SL} is the atmospheric superheat limit (K) and V_L the liquid volume fill level (m^3).

The expression of energy provided is [8,15]:

$$W = 0.024 \frac{P V^*}{k-1} \left[1 - \left(\frac{P_{\text{atm}}}{P} \right)^{(k-1)/k} \right] \quad (10)$$

where W is the equivalent of TNT (kg); P_{atm} and P are the atmospheric pressure and the pressure existing in the tank (bar), respectively; V^* can be expressed as

$$V^* = V_V + V_L^* \quad (11)$$

where V_V is the volume of vapor in the tank (m^3); V_L^* the volume of liquid that can flash just after the moment of rupture and can be expressed as $V_L^* = V_L (f \rho_{\text{Lo}} / \rho_{\text{VT}})$; V_L the actual volume of liquid (m^3); ρ_{Lo} and ρ_{VT} represent the densities of liquid and vapor, respectively, corresponding to the temperature and pressure in the tank (kg m^{-3}). The fraction of liquid f that flashes after depressurization can be expressed as [16,17]:

$$f = \frac{C_p (T_0 - T_b)}{\Delta h_v} \quad (12)$$

where T_0 and T_b represent the initial and boiling temperatures of the liquid (K), respectively; C_p the specific heat capacity ($\text{kJ kg}^{-1} \text{K}^{-1}$); Δh_v the latent heat of vaporization (kJ kg^{-1}).

Eq. (12) is only suitable for the PLG being uniformly heated. However, under some circumstances, the maximum temperature difference can reach 20 K [10]. So stratification should be considered. In our model, the tank is a vertical cylindrical tank whose radius and height are R and H , respectively. Then V_L^* can be given as:

$$V_L^* = \pi R^2 \int_0^{h_L} f \left(\frac{\rho_{\text{Lo}}}{\rho_{\text{VT}}} \right) dx \quad (13)$$

where h_L is the height of the liquid.

Substituting Eq. (12) into Eq. (13), we can get following expression:

$$V_L^* = \pi R^2 \int_0^{\delta_s} \left(\frac{C_p (T - T_b)}{\Delta h_v} \right) \left(\frac{\rho_{\text{Lo}}}{\rho_{\text{VT}}} \right) dx + \pi R^2 (h_L - \delta_s) \left(\frac{C_p (T_0 - T_b)}{\Delta h_v} \right) \left(\frac{\rho_{\text{Lo}}}{\rho_{\text{VT}}} \right) \quad (14)$$

Based on the temperature profile mentioned above, V_L^* can be calculated by the integration of Eq. (14).

4. Discussion of result and experimental verification

4.1. Experimental setup

Small-scale experiments were carried out to verify the stratification model. The experiments were conducted on a test 60 l tank (see Fig. 2). An electric heater that can simulate

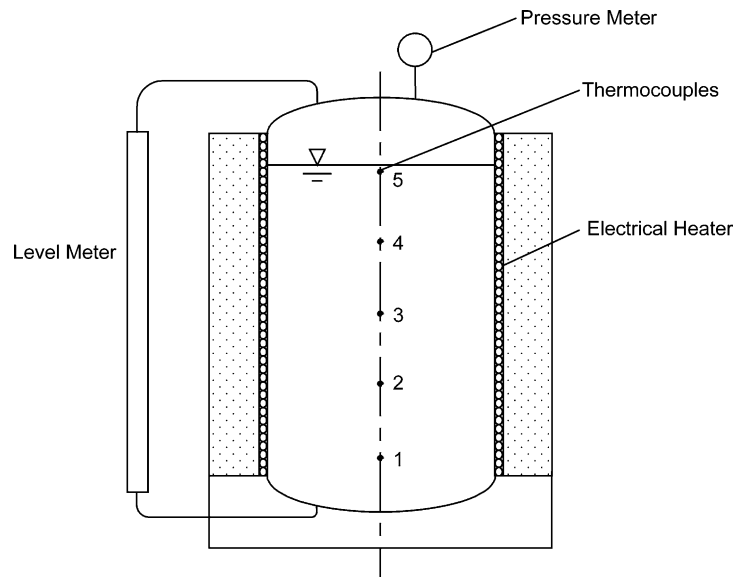


Fig. 2. Experimental setup.

the outer heat impingement wrapped the tank. Compared with the direct exposure to fire impingement, it has two advantages: (1) it is safer because of less chance to fire and explode; (2) the heat flux can be controlled and is uniform. The insulation outside of the heater can ensure that the energy is transferred to the loading efficiently.

The experiments reported here were performed with propane as the working fluid. We waited a long time to keep the temperature of the propane uniform in the tank before experiments began. Temperatures of propane at different points are measured by five T-type thermocouples calibrated with maximum uncertainty of 0.1 K. These thermocouples were mounted with uniform axial distance of 100 mm. All the output of measured values was recorded by a data acquisition system (FLUKE 2620T). The pressure is recorded by a pressure meter with the error of ± 0.05 MPa. The parameters varied during the experiments are the heat flux and the liquid level. When the pressure reaches 2.1 MPa, the heater is shut off.

4.2. Comparison between experiments and model

Simulations have been carried out to evaluate the performance of the stratification model based on the experimental data in this work.

Fig. 3 shows comparisons between model and experiments at different heat flux ($3, 5 \text{ kW m}^{-2}$) under different liquid levels (80, 50%). Assuming that the heat flux rises from zero to the maximum value in 4 min, they are in good agreement. The time for the heat fluxes 3 and 5 kW m^{-2} at the 80% filling to reach 2.1 MPa are 31 and 20 min, respectively. Both the results of the mathematical model and the experimental data indicate that pressure rises faster when the heat flux increases, since more energy enters the strat-

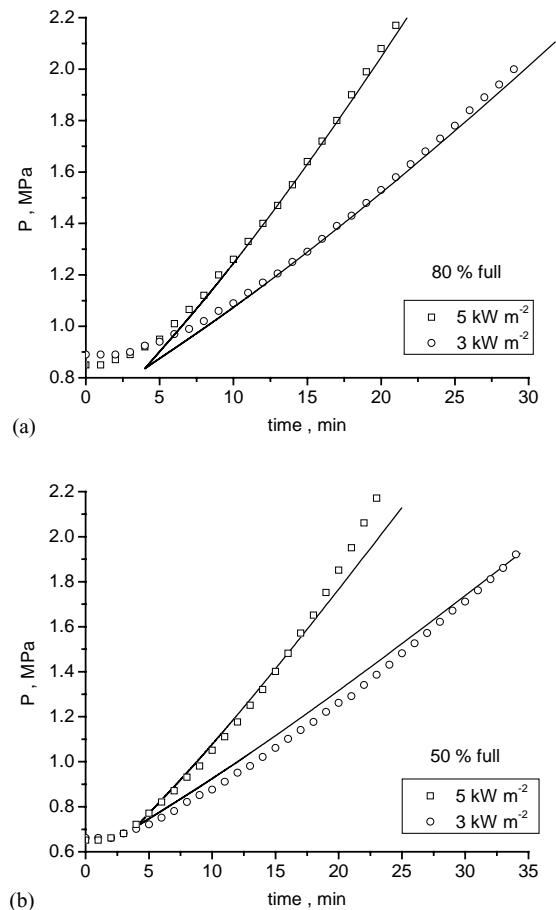


Fig. 3. Comparison between model and experiments for different heat flux: (a) 80% full; (b) 50% full (lines: the stratification model; symbols: experiment).

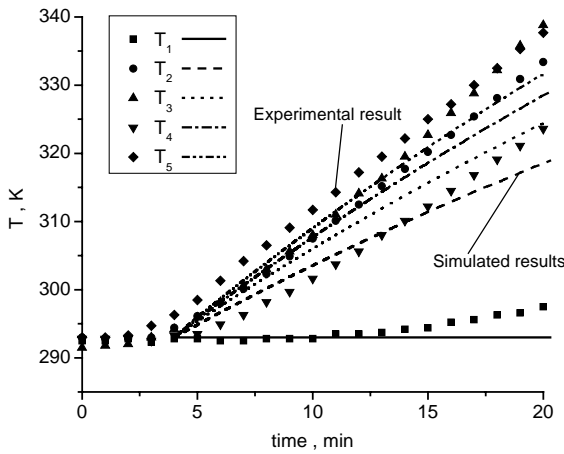


Fig. 4. Temperature vs. time (80% full, 5 kW m^{-2} ; lines: the stratification model; symbols: experiment).

ification layer. As can be seen, the pressure rate increases with the increasing filling percentage. This is mainly because higher filling level results faster development of the stratification layer.

Temperature histories are plotted in Fig. 4 for 80% filling level and 5 kW m^{-2} heat flux. Lines and symbols represent the experimental and simulated results, respectively. T_i ($i = 1, 2, 3, 4, 5$) represents the temperature of thermocouple i . The experimental data verify the prediction that the liquid energy in the stratification layer is exponentially distributed and the temperature at the top of the tank changes faster than that at the bottom. When the internal pressure reaches 2.1 MPa, the maximum temperature difference within liquid can be more than 30 K. The experimental and simulated results show the same trend. The simulated results are lower than the experimental results due to the model does not account for heat added before the heat flux reaches its maximum.

Fig. 5 shows that the time for the pressure to reach 2.1 MPa calculated from two different models, the

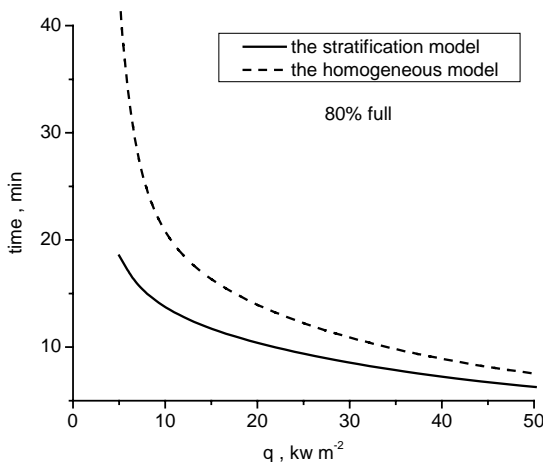


Fig. 5. Time to reach 2.1 MPa at different heat flux.

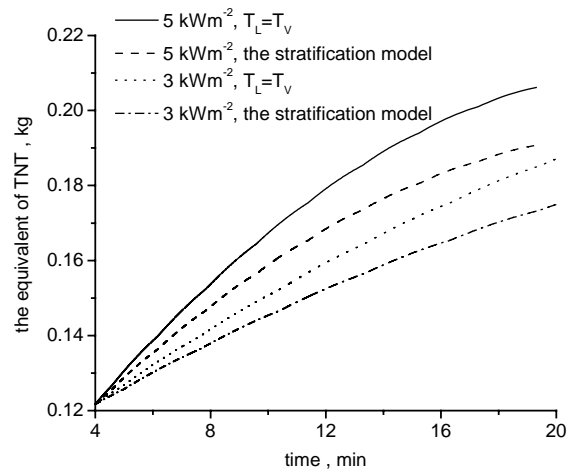


Fig. 6. The energy of liquid (80% full).

stratification model and the homogeneous model that assumes that the temperature is uniform in PLG tank. As can be seen, the pressure in the tank rises faster allowing for stratification, which means the stratification layer reduces the time for the tank to fail, as discovered by other researchers [9].

4.3. The influence of stratification on BLEVE energy

It can be found from the discussions above that the stratification model is capable of correctly predicting the experimental data and can be used to predict the energy in the liquid when a BLEVE occurs. The liquid energy is related to the liquid temperature and the liquid mass in the tank. Fig. 6 shows that the energy increases with the increasing heat flux when the stratification model and the uniform temperature ($T_L = T_V$) model are employed. The energy calculated from the uniform temperature model is greater than that from the stratification model at the same pressure. This is mainly because in the stratification model the top liquid temperature dictates the pressure in the tank. Increasing the thermal stratification can enlarge the difference between the results of the stratification model and the uniform temperature model. That is the reason that some means [18] are advised to have the stratification increased.

5. Conclusion

A simple model has been developed to investigate the effect of the thermal stratification on the thermal response. Comparison between the simulation result and the experimental data shows that the simplified solutions can reasonably predict the pressure and temperatures in the tank. The temperatures can then be used to calculate the liquid energy. The degree of thermal stratification influences the rate at which the pressure in the tank rises and the liquid energy. Increased thermal stratification decreases the severity of the hazard when BLEVE occurs.

Acknowledgements

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