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Rollover of Liquid Natural Gas in a Storage Tank: A Numerical Simulation

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Abstract. In the filling and transportation processes of liquefied natural gas (LNG), the safety of LNG storage tanks is compromised because of rollover phenomenon. As such, the rollover factors of LNG in a storage tank should be identified to prevent or weaken the rollover intensity of LNG. In this study, the rollover behavior of LNG in a storage tank is numerically simulated. The density of the two layers in a LNG storage tank is related to temperature in our numerical model. It is found that the greater the significant initial density difference (range of 1-12 kg·m^{-3}) is, the more obvious the LNG rollover will be. A density difference of 7.5 kg·m^{-3} is found as the critical density difference in the present work. When the initial density difference exceeds the critical density difference, the LNG rollover coefficients increase dramatically. Moreover, an LNG rollover model with two daughter models is proposed, which are divided by the critical initial density difference, i.e., a cubic relationship between rollover coefficients and the initial density difference when the density difference is less than 7.5 kg·m^{-3} and secondly, a linear relationship between the rollover coefficient and the double exponential functions when the density difference is larger than 7.5 kg·m^{-3}.

Keywords. LNG, rollover, density, critical density difference

1. Introduction

Liquid natural gas (LNG) is usually stored and transported in a liquid form at nearly atmospheric pressures and at temperatures close to -162 °C. When LNG is injected into storage tanks and mixed with the residual LNG, LNG stratification appears. Soon after, rollover occurs because of stratified liquids in storage systems [1-3]. Two well-known rollover accidents occurred in the Snam LNG Distribution Station and the Partington LNG Pitch Peak Station in 1971 and 1993, respectively [4, 5] Considering the two serious events, many researchers studied the mechanism of LNG rollover and suppression measures although previous related studies were conducted even before the two incidents happened [6-10]. In 1972, Chatterjee and Geist [7] first proposed a rollover model, i.e., the C-G model. Then, Heestand [9] developed the C-G model and obtained the HSM model. In 1993, Shi et al. found a migrating interface from experiments [11]. Thereafter, a rollover model that first considered the liquid interface as a dynamic state was established [12-15].

Previous rollover investigations preferably explained the evolution from stratification formation to rollover occurrence. Few models have been proposed to describe the rollover coefficients of stratified LNG layers. Therefore, the mechanism of

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LNG rollover should be studied to accurately predict the relationship between rollover coefficients and density and ensure the safety of LNG storage tanks.

2. Numerical Models of LNG Rollover

2.1. Description of the Geometric Model of LNG Rollover

In our geometric model of LNG rollover, LNG is injected into a storage tank that already contains a stored LNG. A 2D LNG storage tank is presented as figure 1.

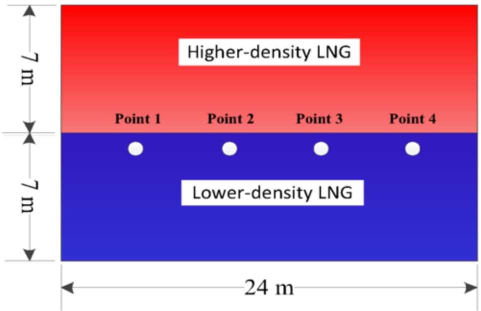


Figure 1. Geometric model of a stratified LNG.

2.2. Mathematical Model and Governing Equations

(1) Continuous equations

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

(2) Momentum equations

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \left(\nu + \nu_{\mathrm{t}}\right)\nabla^2 u_i + F_i \tag{2}$$

(3) Energy equations

$$\rho C_{\mathrm{p}}\left(\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i}\right) = \lambda \frac{\partial^2 T}{\partial x_i^2} \tag{3}$$

(4) Composition equations

$$\rho \frac{\partial S}{\partial t} + \rho u_j \frac{\partial S}{\partial x_i} = \rho D_{\mathrm{AB}} \frac{\partial^2 S}{\partial x_i^2} \tag{4}$$

(5) Density equations

$$\rho \approx \rho_0 \left[1 - \beta \left(T - T_0 \right) \right] \tag{5}$$

where $\beta = 0.00341$ is the thermal expansion coefficient.

The initial densities of the upper ($\rho_{0\mathrm{H}}$) and lower ($\rho_{0\mathrm{L}}$) layers of LNG are written as follows [16]:

$$\rho_{0\mathrm{H}} = -1.24T + 586.49 \tag{6}$$

and

$$\rho_{0\mathrm{L}} = -1.33T + 573.35 \tag{7}$$

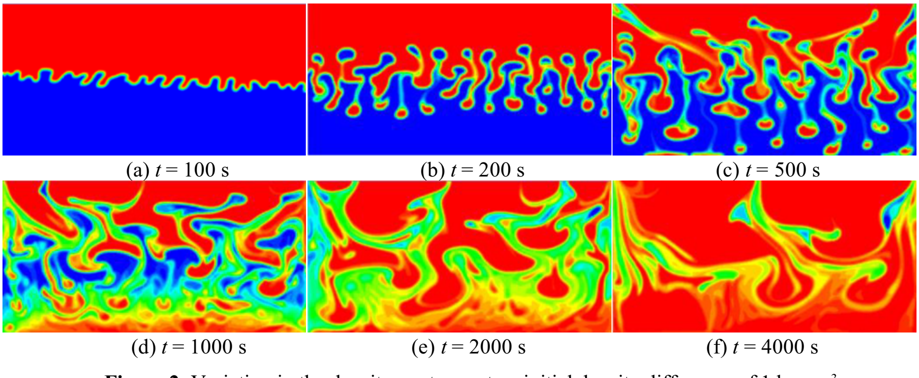
In addition, the widely used turbulent model $k-\varepsilon$ is employed. The top of the tank is pressure outlet, and the others is wall with a constant value of 30 W·m^{-2}.

3. Results and Discussion

3.1. Variations in Density Contours with Time

The density of the lower LNG layer is a constant value of 425 kg·m^{-3}. The density of upper layer is larger than that of the lower layer, and the initial density difference is between 1 and 12 kg·m^{-3}. The variations in density contours with time at initial density differences of 1, 5 and 10 kg·m^{-3} are compared (figures 2-4).

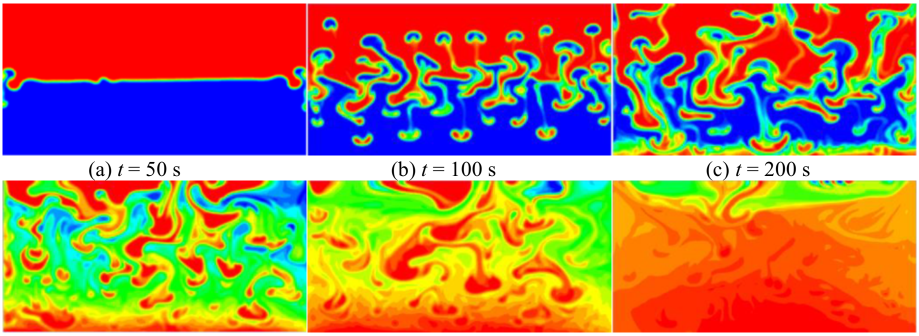
At the beginning of the mix, the upper LNG layer seems to drop to the lower LNG layer, and the bottom layer LNG drops and moves upward at the same time. Then, the two layers mix gradually. The density of LNG tends to be identical over time because of the heat transfer between the two LNG layers, including heat leakage from the storage outside the storage tank. With careful observation, as the initial density difference widens, the mixing time shortens. For example, the density contours at 1000, 200, and 100 s in figures 2d, 3c, and 4c are similar.



(a) t = 100 s (b) t = 200 s (c) t = 500 s

(d) t = 1000 s (e) t = 2000 s (f) t = 4000 s

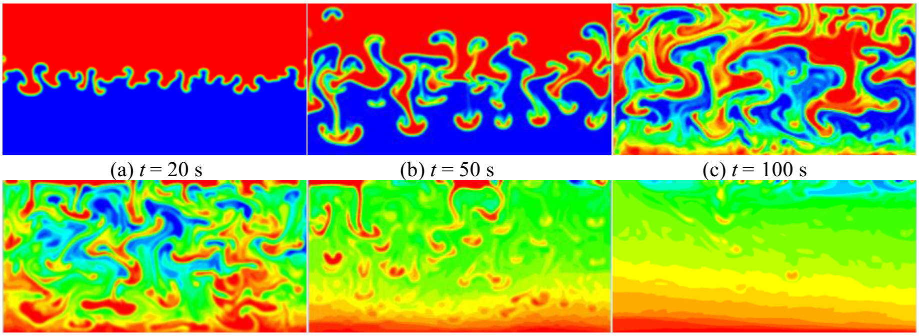
Figure 2. Variation in the density contours at an initial density difference of 1 kg·m^{-3}.



(a) $t = 50$ s (b) $t = 100$ s (c) $t = 200$ s

(d) $t = 500$ s (e) $t = 800$ s (f) $t = 2000$ s

Figure 3. Variation in the density contours at an initial density difference of 5 kg·m^{-3}.



(a) $t = 20$ s (b) $t = 50$ s (c) $t = 100$ s

(d) $t = 150$ s (e) $t = 500$ s (f) $t = 1000$ s

Figure 4. Variation in the density contours at an initial density difference of 10 kg·m^{-3}.

3.2. Variations in Density Contours with Initial Density Difference

Figure 5 describes the LNG density contours at 100 s. The greater the initial density difference is, the more violent the LNG rollover will be. Therefore, the preferred method of controlling LNG rollover is shortening the initial density difference between the injected LNG and the residual LNG in the storage tank.

3.3. Influence of the Initial Density Difference on LNG Rollover Coefficients

According to the model of Li et al. [17], the LNG rollover coefficient is written as

$$f = \frac{|\Delta\rho_{\max} - \Delta\rho|}{t} \quad (8)$$

LNG rollover coefficients vary with the initial density difference (figure 6).

In particular, the LNG rollover coefficient dramatically changes when the initial density difference exceeds a critical density difference of 7.5 kg·m^{-3}. The critical density difference ($\Delta\rho_c$) can be converted into the critical temperature difference (ΔT_c) by using the following equation [17]:

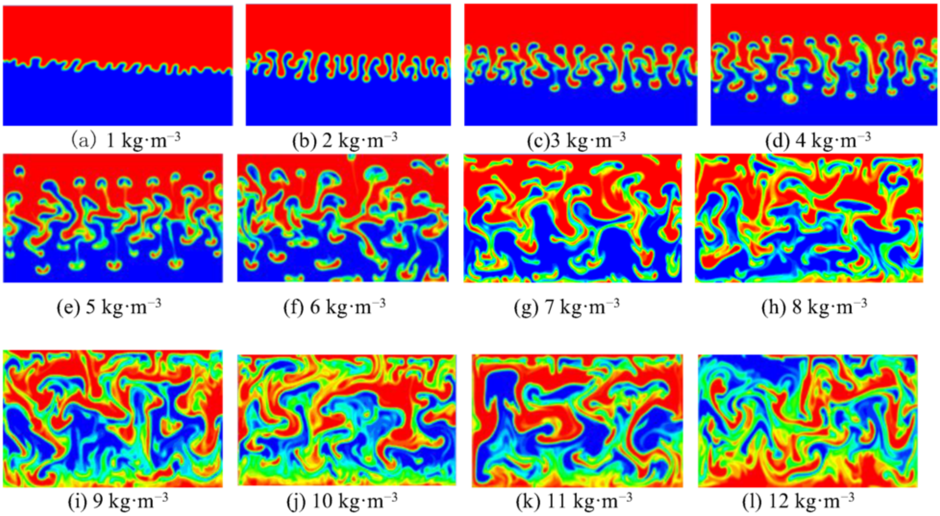


Figure 5. Contours of LNG rollover for different density differences at 100 s.

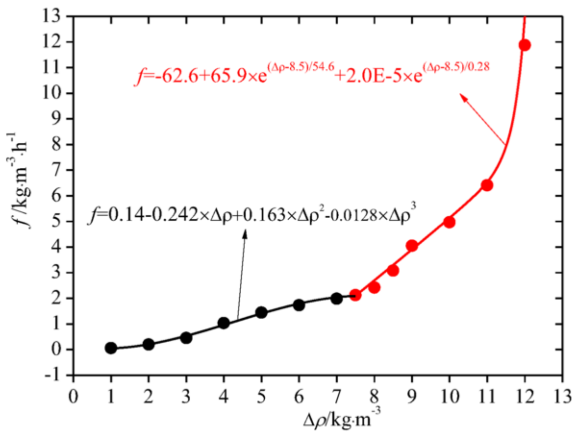


Figure 6. LNG rollover coefficients vary with initial density difference.

$$\Delta\rho_c = 1.35\Delta T_c \tag{9}$$

Here, the critical temperature ΔT_c = 5.5 K when $\Delta\rho_c = 7.5$ kg·m^{-3}.

Li et al. [17] also proposed a model to describe the relationship between the volume (V) of LNG and ΔT_c:

$$\Delta T_c = -0.855 \ln V + 12.48 \tag{10}$$

V of the present numerical LNG storage tank is 6333 m^3, and its ΔT_c is 5.0 K. The error between the present critical density difference and the theoretical model is 10%, which is within an acceptable range.

At the initial density difference less than 7.5 kg·m^{-3}, the LNG rollover coefficients are expressed as:

$$f = 0.14 - 0.242 \cdot \Delta\rho + 0.163 \cdot \Delta\rho^2 - 0.0128 \cdot \Delta\rho^3 \tag{11}$$

At the initial density difference larger than 7.5 kg·m^{-3}, the rollover coefficients increase dramatically as:

$$f = -62.6 + 65.9 \cdot \exp\left[\left(\Delta\rho - 8.5\right)/54.6\right] + 2.0\mathrm{E}-5 \cdot \exp\left[\left(\Delta\rho - 8.5\right)/0.28\right] \tag{12}$$

4. Conclusions

A numerical method is used to simulate the rollover behavior of LNG in a storage tank. The conclusions can be summarized as follows.

(1) When the higher-density LNG is injected into the storage tank, the LNG rollover rapidly occurs. The greater the initial density difference is, the more violent the LNG rollover will be. In rollover process, the upper layer drops first, and the bottom layer drops and moves upward. Subsequently, the two layers mix gradually. Lastly, the mixed LNG achieves a steady state.

(2) The development process of LNG rollover is directly controlled by the initial density difference. A density difference of 7.5 kg·m^{-3} is proposed as the critical density difference. When the initial density difference achieves and exceeds the critical point of 7.5 kg·m^{-3}, the LNG rollover coefficients increase dramatically.

(3) The rollover coefficient model consists of two parcels, i.e., a cubic relationship between rollover coefficients and the initial density difference when the density difference is less than 7.5 kg·m^{-3} and secondly, a linear relationship between the rollover coefficient and the double exponential functions when the density difference is larger than 7.5 kg·m^{-3}.

Acknowledgment

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