ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 43 (2012) 472 – 477
Procedia Engineering
www.elsevier.com/locate/procedia

# International Symposium on Safety Science and Engineering in China, 2012 (ISSSE-2012)

# CFD Simulation of Temperature Field Distribution of the Liquefied Hydrocarbon Spherical Tank Leaking

Ling Xiaodong[a,b*], Han Zhongshu[a,b], Dang Wenyi[a,b], Yu Anfeng[a,b], Wang Peng[a,b]

[a]*SINOPEC Research Institute of Safety Engineering, Qingdao Shandong, China*
[b]*State Key Laboratory of Safety and Control for Chemicals, Qingdao Shandong, China*

## Abstract

Liquefied hydrocarbon is normally stored under high pressure in overheating state in the spherical tank. Once leakage occurs, the liquefied hydrocarbon will quickly gasify and absorb a great deal of heat, making temperature of spherical tank decrease sharply. In order to investigate this process, physical model was established, and the Reynolds time averaged Navier-Stokes equation and k-ε turbulent model as the CFD simulation method were used in this study. The temperature distribution of the spherical tank and the environment after spherical tank pipeline leaking was analyzed. The influences of leakage location and leak area on the spherical tank temperature distribution were analyzed, and a meaningful conclusion was obtained. This study could provide theoretical basis and technical support for the safety control of liquefied hydrocarbon spherical tank leakage.

*Keywords*: Liquefied hydrocarbon, Spherical tank , Leakage , Temterature, CFD simulation

**Nomenclature**

| | |
|---|---|
| $\mu$ | dynamic viscosity fluid turbulent |
| $k_{eff}$ | effective transmission coefficient |
| $J_j$ | the spread of components j for traffic |
| $M_j$ | the mass fraction of component j |
| $\rho_m$ | mixture densities |
| $G_{k,m}$ | turbulent kinetic energy produce items |

## Introduction

As an important facility in chemical production process, the number of liquefied hydrocarbon spherical tank increases rapidly. With the characteristics of inflammability, explosion and toxicity, liquefied hydrocarbon have potential risks in the producing, using, storage and transport process, so it is very necessary to pay more attention to its safety. Once the material or energy was in an abnormal condition, the device may explode, and big losses on the staff's life, property and the

---

* Corresponding author. Tel.:0532-83786094.
E-mail address:Lingxd.qday@sinopec.com

doi:10.1016/j.proeng.2012.08.081

environment may occur as a result, which will lead to catastrophic consequences [1]. For example, in 1998, liquefied gas explosion in Xi'an caused seven fire fighters and five staffs killed, 32 people wounded, and 4.8 million RMB's economic loss [2]; In 2010, liquefied hydrocarbon fire and explosion accident of Lanzhou petrochemical caused six people killed, and six people injured. Eight vertical storage tanks and two spherical tanks were damaged in this accident.

In China, the material of some in-service propylene and propane spherical tanks is 16MnR or the steel that is equivalent with 16MnR [3]. The low temperature limit of 16MnR is -20 ℃. Compared with this, the boiling point of propylene and propane are respectively -47.7 ℃ and -42.1 ℃. Once leakage occurs, overheated liquefaction hydrocarbon discharges and gasify sharply, making the spherical tank temperature decrease quickly. If the temperature of tank shell decreases below the low temperature limit of 16MnR, the spherical tank will suffer brittle fracture, and cause serious accidents.

In order to evaluate the risk assessment of leakage accident and improve protection measures, liquefied hydrocarbon leaking model was conducted, and the temperature change of the tank with different leak area was simulated using CFD method.

## 1. The mathematical model and the basic equation

### *1.1. Basic conservation equation*

Liquefied hydrocarbon is highly pressurized in the spherical tank, once leakage occurs, the liquefied hydrocarbon flow blowing through the leak point was turbulent, therefore the liquefied hydrocarbon flow control equation for Reynolds time-average method are as follows [4]:

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}) \tag{2}$$

The energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(u_i \rho E) = \frac{\partial}{\partial x_i}(k_{eff} \frac{\partial T}{\partial x_i} - \sum_j h_j J_j) \tag{3}$$

$$E = h - \frac{p}{\rho} + \frac{u_i^2}{2} \tag{4}$$

$$h = \sum_j m_j h_j \tag{5}$$

$$h_j = \int_{T_{ref}}^{T} C_{p,j} dT \tag{6}$$

The equations above constitute the liquefied hydrocarbon flow and heat transfer process control equations. The equations contain unknown correlation term, and do not constitute a closed system. With the right turbulence model the equations could be closed.

### *1.2. Turbulence model*

The variables in the control equations represent the instantaneous velocity in the flow field. For turbulent flow, instantaneous value is not measureable. Only time-average value, which is concerned in practical engineering, can be obtained. So Reynolds time-average method makes instantaneous equations simplified. The high order unknown correlation term can be replaced with low order unknown correlation term or time-average value. In this way the Reynolds time-average equation can be closed and solved [5]. The most popular turbulence model is the k-ε two equation turbulence model, which uses mixed properties and mixed speed to capture the important features of turbulence [6]. The equations of k-ε model are as follows:

$$\frac{\partial}{\partial t}(\rho_m \kappa) + \nabla(\rho_m \vec{u}_m \kappa) = \nabla(\frac{\mu_{t,m}}{\delta_\kappa} \nabla \kappa) + G_{k,m} - \rho_m \varepsilon \tag{7}$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon)+\nabla(\rho_m \vec{u}_m \varepsilon)=\nabla(\frac{\mu_{t,m}}{\sigma_\varepsilon}\nabla\varepsilon)+\frac{\varepsilon}{k}(C_{1\varepsilon}G_{k,m}-C_{2\varepsilon}\rho_{m\varepsilon}) \tag{8}$$

## 2. Device parameters and simulated condition

### 2.1. Device parameters

One liquefied hydrocarbon spherical tank in a spherical tank zone was studied, and the capacity of this spherical tank is 1000 $m^3$, with 12.3 m internal diameter, filled with propane, internal temperature of 36 ℃, and internal pressure 1.4 MPa.

### 2.2. Simulated condition

According to preliminary research and the data obtained from the field, 12 different leak scenes formed by three kinds of leakage area and four different leakage points were designed as follows:

Three leakage areas: The percentages of the leakage area accounts for pipeline cross-sectional area are 10%, 20%, 100%, respectively.

Four different leak points: the leak was assumed to occur on the export pipeline, and the distances from the leak point to the spherical tank are 0.25m, 0.50m, 0.75m, and 1.00m, respectively.

### 2.3. Mesh generation

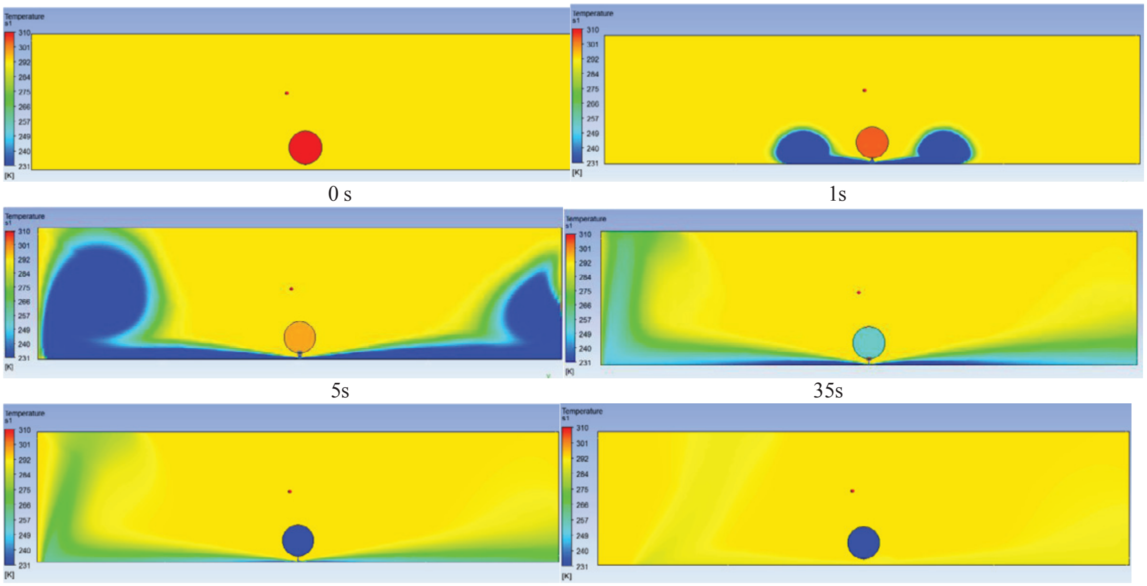
All the liquid hydrocarbon spherical tank leakage physical models which were discretely processed with structured and unstructured grids combining mesh generation method were established using Gambit. Using the unstructured grids, the grid size around the leak point is much smaller than the size of the other part of the model in order to obtain good quality mesh. For non-critical area, using structured grid can get high quality mesh with low deformation degree and less quantity.

## 3. Results

### 3.1. The distributions of temperature

Fig 1 shows the change of temperature distributions of liquefied hydrocarbon spherical internal and the surrounding environment with time. The percentage of the leakage area accounts for pipeline cross-sectional area is 100%, and the distance of the leak point from the spherical tank is 0.25 m.

According to the calculating results above, the internal temperature of the spherical tank was 36 ℃ while the outside of the spherical tank is 20 ℃ at the very beginning of leaking. One second later, an area of 35 meters long and 15 meters high with low temperature was formed near the leak point. The lowest temperature of this area was 231K (-42 degrees Celsius), and temperature gradient could be observed along the outboard of the area. And also temperature gradient can be observed near the leak point. Temperature of the spherical tank was also reduced, and the temperature of the leak point is about 304K (30 degrees Celsius). Five seconds later, the low temperature area extended significantly, reaching a height of 50 meters and a width of 100 meters, and the tank temperature reached 298K (25 degrees Celsius). About 35 seconds later, low temperature area kept on expanding, and the temperature within spherical tank continued to fall, reaching 254K (-19 degrees Celsius) which was lower than the temperature limit of the ordinary steel. If the spherical tank was shocked or hit at the moment, brittle fracture would happen. After 55 seconds, the low temperature zone outside of the spherical tank reduced gradually, and only near the leak point and ground a small area of low temperature zone was left. While the temperature in the spherical tank still decreased gradually, and the temperature at most part of the tank reduced to 231K (-42 degrees Celsius) which was just the condensation temperature of propane at the atmospheric pressure. 100 seconds later, the external temperature gradually back up to the initial temperature because of huge heat capacity of the atmosphere, while the temperature of the spherical tank kept low.



0 s 1s

5s 35s

55s 100s

Fig. 1. Changing with time of temperature distributions of liquefied hydrocarbon spherical internal and surrounding environment.

### 3.2. Internal temperature change of the spherical tank

Other temperature distributions of spherical tank leaking scenes were also studied. In order to get the temperature variation curve of the spherical tank, monitoring points was set at the bottom of the spherical tank. The calculating results are shown as Fig.2 to Fig.5.

Simulation results showed that, the temperature reduction rate in spherical tank with the same leak position was proportional to the leakage area, and the less of the distance from spherical tank to the leak point, the faster of the temperature reduction of spherical tank. When the temperature of the spherical tank dropped to -42 ℃ which was the condensing temperature of propane at atmospheric pressure, the propane did not gasify or absorb heat, so the internal temperature of the spherical tank did not change.

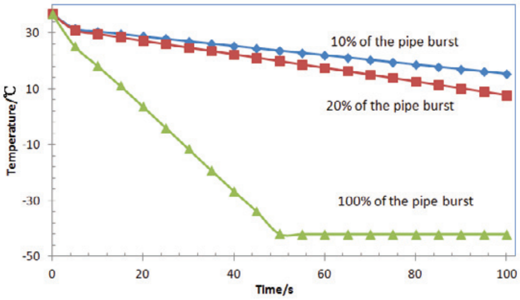


Fig. 2. The temperature curves varying with time when the distance from leak point to the spherical tank was 0.25m.

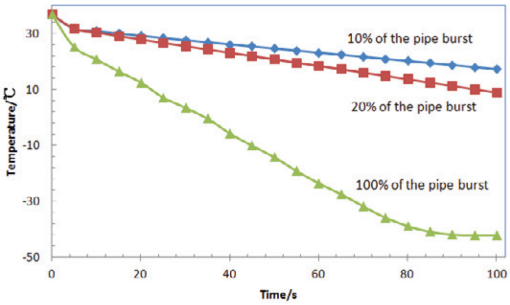


Fig. 3. The temperature curves varying with time when the distance from leak point to the spherical tank was 0.50m.

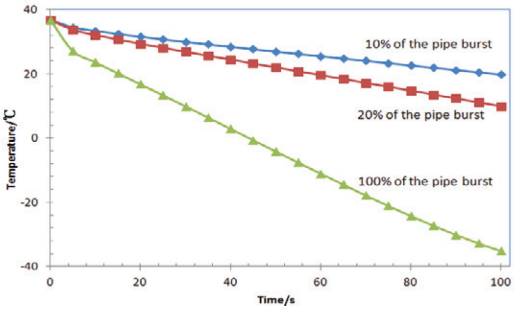


Fig. 4. The temperature curves varying with time when the distance from leak point to the spherical tank was 0.75m.

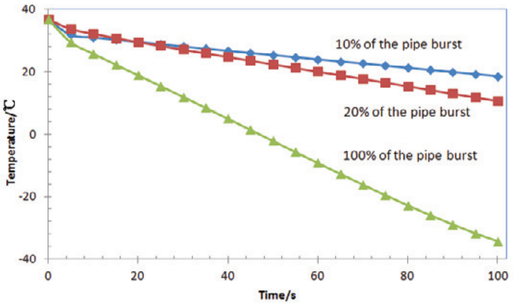


Fig. 5. The temperature curves varying with time when the distance from leak point to the spherical tank was 1.00m.

### *3.3. The time required for spherical reach certain key temperature*

According to the calculating results above, the temperature drop was linear with leaking time before reaching propane's condensate temperature. The temperature drop rate and leaking time was fitted, and the time required for the spherical tank reaching certain temperature could be predicted with the fitting curve as shown in Table 1.

Table 1. The time required for the spherical tank reaching the certain temperature under different conditions (s).

| Distance from leak point to the spherical tank | 0.25m | | | 0.50m | | | 0.75m | | | 1.00m | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10% | 20% | 100% | 10% | 20% | 100% | 10% | 20% | 100% | 10% | 20% | 100% |
| 0 | 182.4 | 128.7 | 22.5 | 204.3 | 134.8 | 34.8 | 224.3 | 137.9 | 45.2 | 220.5 | 142.4 | 47.7 |
| -20 | 292.8 | 206.6 | 34.9 | 327.8 | 215.3 | 58.1 | 352.5 | 217.1 | 74.3 | 353.5 | 224.1 | 76.4 |
| -42 | 414.4 | 292.5 | 50.0 | 463.6 | 304.0 | 83.6 | 493.4 | 304.1 | 106.3 | 500 | 313.9 | 108.1 |

It has important practical significance for the actual liquefied hydrocarbon safety control technology to know the time required for the spherical tank reaching the following three key temperatures.

An important method to stop spherical tank leak is water injection plugging technology. When the temperature of the liquefaction spherical tank is above 0 ℃, this method will work properly. If spherical tank's temperature decreased below 0 ℃ , the water would freeze and no liquidity, this method will fail.

Most of the material of the in service propane spherical tanks are 16MnR, and the low temperature limit of 16MnR is -20 ℃. When spherical tank leakage time is more than the time required for spherical tank reaching -20 ℃, spherical tank ductility decreased, brittle fracture may occur.

The boiling point of propane is -42 ℃, if the temperature inside of the spherical tank is down to -42 ℃, the propane within the spherical tank will no longer be gasified, this is the low temperature limit of propane leakage.

## 4. Conclusion

In this paper physical models were established according to the leaking process of the spherical tank, the temperature distribution of the spherical and the environment after spherical tank pipeline leaking with the CFD simulation method was analyzed. The simulation results show that, the spherical tank temperature reduction rate was proportional to the leakage area, and inversely proportional to the distance of leak point from the spherical tank. The time required for the spherical tank reaching the certain temperature under different conditions was also predicted, which could provide theoretical basis and technical support for the safety control of liquefied hydrocarbon spherical tank leakage.

## 5. References

[1] Liu Xueying, Cui Qibi, Jing Guoxun,2008. Large Liquefaction Hydrocarbon Tank Field Hazard Analysis and Control, Journal of Shanghai Institute of Technology(Natural Science) 4.

[2] Lu Chaorong, Zhang Yongguo,1999. Xian Liquefied Gas Explosion Accident Process and Analysis, Oil & Gas Storage and Transportation 10.
[3] Liquid Hydrocarbon Spherical Tank Zone Special Assessment Report of Sinopec.
[4] Tao Wenquan,2001. The Numerical Heat Transfer, Xi 'an Jiaotong University Press, CHINA.
[5] He Xia,2008. The Simulation Study on Gas-solid Flow Behavior in FCC Settlement and the Influence on Cooking (Master's Degree Thesis), China university of petroleum, CHINA.
[6] Chen Yonghui. Wang Qiang, Pu Xiangbo,2009. The Development of Turbulence Model and the Present Situation. Energy and environment 2.
[7] Wu Ceyu, Liu Yongqiang,2011. Applied Analysis Water Injection System of Liquefied Hydrocarbon Spherical Tank. Safety Health & Environmen 4.