LNG ACCIDENT DYNAMIC SIMULATION: APPLICATION FOR
HAZARDOUS CONSEQUENCE REDUCTION

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ABSTRACT

The definition of hazard area, centered inside the LNG stations, is essential for risk assessment in LNG industry. In this study, computational fluid dynamics (CFD) simulations have been conducted for the two main LNG hazards, LNG flammable vapor dispersion and LNG pool fire radiation, to determine the hazard exclusion area. The spatial and temporal distribution of hazard in complex spill scenario has been considered in CFD model. With the developed CFD code, the spray water curtains were studied as a shield to prevent LNG vapor dispersing. Two types of water spray curtain, flat curtain and cone, were analyzed to show their performance for reduction and minimization of the hazard influencing distance and area. The high expansion foam firefighting process was also studied with dynamic simulation of the foam action. The characteristics of the foam action on the reduction of LNG vaporization rate, vapor cloud and flame size as well as the thermal radiation hazard were analyzed and discussed.

1. INTRODUCTION

Large quantities of LNG liquid could give off cryogenic and flammable vapor once released. In LNG industry, safety concern for LNG station siting, construction and production has been raised highly because of potential risk of LNG release hazards [1, 2]. One of the most important factors in risk assessment is the prediction of the exclusive distance of inside and outside of LNG plant [3]. For public safety, the two typical hazards upon LNG release, LNG vapor dispersion and LNG pool fire radiation, have gained most attention [4].

Since 1960s, large-scale field tests of LNG release and its resultant hazards have been conducted to study the important physical phenomena [5, 6]. Specifically, experiments of LNG vapor dispersion, as well as LNG fires have been performed during later 1980s [7]. The experimental data have been used to validate mathematical models, including integral model and computational fluid dynamics (CFD) models. The CFD models, which include detailed description of flow physics, are more computationally intensive but are capable of modeling various phenomena adequately. The CFD models have gained increasing interest for analyses of LNG spill hazards. Sutton, Brandt, and White [8] were among the first to apply CFD method to simulate dense gas dispersion in a boundary-layer wind tunnel. Since 1990s, commercial CFD softwares, such as FEM 3 [9], FLACS [10], Star-CD, FLUENT [11] and CFX [12], have become popular and were widely applied to simulate LNG spill hazards.

This study deals with the spatial and temporal CFD simulations of the two typical LNG release resultant hazards, vapor dispersion and fire radiation. Besides, mitigation methods of LNG releases were studied, spray water curtain and high expansion foam working on LNG vapor dispersion and LNG pool fire, respectively. Commercial code FLUENT 13.0 was applied to establish the CFD model of LNG hazards.

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Theory basis of these models can be referred to Ref [13].

2. VALIDATION OF CFD MODELING ON LNG HAZARDS

2.1 CFD model validation for LNG vapor dispersion

Falcon series of LNG vapor dispersion field tests were performed in 1987 [14] by the Lawrence Livermore National Laboratory (LLNL). This study used the experimental data from Falcon tests to validate CFD model of LNG vapor dispersion. Another field test, Montoir series of LNG pool fire tests, performed in 1987 [15], was applied to validate CFD model of LNG pool fire. In the Falcon tests, LNG was released onto the surface of a rectangular water pond, 60 m long and 40 m wide. The water was recycled in order to fully vaporize LNG. A “billboard” stood in front of the water pond, which behaved as the LNG storage tank. The pond was surrounded by a fence, 8.7 m high, 88 m long and 44 m wide, behaving as the impoundment wall.

Monin-Obukhov theory was applied to describe the atmospheric stability, in order to calculate the vertical profile of ambient wind velocity in the boundary layer [16]. A steady-state solution was first sought for the ambient velocity field, as shown in Fig. 1. Swirls were generated inside the impoundment area, which would influence the vapor dispersion.

![Figure 1. Horizontal and vertical velocity field as initial conditions](image1)

![Figure 2. Footprint of LNG vapor cloud dispersion in downwind distance (iso-concentration 2.5% (vol))](image2)

The time-dependent simulation was then performed, initialized by the steady-state simulation. Swirls dragged the dispersed cloud upwind at the beginning of LNG spill, shown in Fig. 2.
Fig. 3 illustrated the comparison of vertical volumetric concentration between test and simulation, located 150 m downwind. The maximum value was almost consistent with experimental data.

Fig. 4 compared the evolution of the predicted value and measured value of gas concentration at 50m and 150m downwind of the impoundment, respectively. It showed that CFD simulation captured the general dispersion behavior of LNG vapor cloud.

2.2 CFD model validation for LNG pool fire radiation

Among the different types of LNG fire, LNG pool fire happened in a higher frequency. The CFD model for LNG pool fire was verified by Montoir series of field test\[15\]. LNG spilled on a 35 m diameter insulated concrete dike. Tab. 1 listed the experimental conditions of three tests. Test 1 and 2 were applied to verify the CFD model of thermal radiation. Fig. 5 illustrated the temperature contours and radiant emissive power iso-profile in Montoir 1 test. A parameter study of flame length vs. iso-temperature surface was implemented and iso-temperature surface of 1100 K was defined as flame outer surface. Comparison of the predicted value of LNG pool fire characteristics and experimental data was listed in Tab. 2. The maximum relative error was lower than 10%.

<table>
<thead>
<tr>
<th>No.</th>
<th>LNG Spill (m³)</th>
<th>Component (% mole)</th>
<th>Wind velocity (m/s)</th>
<th>Temp. (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>238</td>
<td>CH₄ 90.33, C₂H₆ 8.95, C₃H₆ 0.342, N₂ 0.341</td>
<td>2.7-4.8</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>198</td>
<td>CH₄ 89.90, C₂H₆ 8.70, C₃H₆ 0.80, N₂ 0.42</td>
<td>7.0-10.1</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>196</td>
<td>CH₄ 90.10, C₂H₆ 8.91, C₃H₆ 0.64, N₂ 0.266</td>
<td>2.8-4.8</td>
<td>14</td>
</tr>
</tbody>
</table>
Comparison of horizontal radiant power profile was demonstrated in Fig. 6. The downwind and crosswind fire radiant distance had a higher relative error. The total average relative error was 8.75%.

Table 2. Comparison of predicted value and experimental data in Montoir series tests

<table>
<thead>
<tr>
<th></th>
<th>Montoir 1 test</th>
<th>Montoir 2 test</th>
<th>Montoir 3 test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Predicted value</td>
<td>Relative error (%)</td>
</tr>
<tr>
<td>Flame length (m)</td>
<td>75.1±7.1</td>
<td>77.0</td>
<td>2.53</td>
</tr>
<tr>
<td>Average emissive</td>
<td>260.5±6.4</td>
<td>251.2</td>
<td>3.57</td>
</tr>
<tr>
<td>power (kW/m²)</td>
<td>Flame tilted angle (°)</td>
<td>47.0±9.9</td>
<td>45.2</td>
</tr>
</tbody>
</table>

The mitigation of accidental LNG releases had gained a great concern in the LNG industry. Spray water curtain was one of the commonly used methods to block LNG vapor dispersion\(^{[17]}\). The mitigation effects of the two types of spray curtain, flat curtain and cone curtain were studied. The fan nozzle was capable to project a fan-shaped water curtain in 180°. According to the product specification from Angus\(^{[18]}\), the flat curtain could cover approximate 24.4 m wide in crosswind and 7.6 m high. The other type of water curtain, 60° cone curtain, was constructed by a full cone spiral nozzle. The cone nozzles were usually designed in a line in the downwind of LNG vapor dispersion, which behaved as a porous block.

3. MITIGATION METHOD ON LNG VAPOR DISPERSION

The mitigation of accidental LNG releases had gained a great concern in the LNG industry. Spray water curtain was one of the commonly used methods to block LNG vapor dispersion\(^{[17]}\). The mitigation effects of the two types of spray curtain, flat curtain and cone curtain were studied. The fan nozzle was capable to project a fan-shaped water curtain in 180°. According to the product specification from Angus\(^{[18]}\), the flat curtain could cover approximate 24.4 m wide in crosswind and 7.6 m high. The other type of water curtain, 60° cone curtain, was constructed by a full cone spiral nozzle. The cone nozzles were usually designed in a line in the downwind of LNG vapor dispersion, which behaved as a porous block.
The basic characteristics of the two types of nozzles were displayed in Fig. 7. The cone nozzles could create smaller water droplet. A semi-empirical correlation, the Ergun equation \(^{(19)}\), was referred to calculate the coefficients of viscous resistance, \(C_v\), and inertial resistance, \(C_i\), which were described in Eqn. 1.

\[
C_v = \frac{1.5(1-\varepsilon)^2}{D_p^2\varepsilon^3}, \quad C_i = \frac{3.5(1-\varepsilon)}{D_p\varepsilon^3}
\]

(1)

Where \(D_p\) is the diameter of water droplet in curtain; \(\varepsilon\) is void fraction in curtain, which equals 1.0 at the spray center and equals 0.0 at the edge of curtain. The resistance coefficients were summarized in Fig. 8.

The steady-state velocity field was obtained first and the results were demonstrated in Fig. 9. Swirls were generated in both vertical and horizontal, which made the dispersed vapor to move towards the swirl’s center and mitigated the hazardous area to a large degree.
Fig. 10 compared the hazard influencing area of scenarios of flat curtain, cone curtain and no curtain, assuming the ambient conditions were the same. Iso-concentration surface of 2.5% was the most concerned, because exclusive distance would build at the downwind edge of this concentration, according to NFPA 59A (2009 Edition) [20]. The results showed that if there was no water curtain existed, the exclusive distance was 82.0 m downwind. The flat curtain helped to reduce the distance by 83.9 %, while the cone curtain reduced the distance by 61.0%.

4. MITIGATION METHOD ON LNG POOL FIRE RADIATION

Commonly used mitigation method in LNG industry was high expansion (HEX) foam, especially for reducing the hazard from LNG pool fire [21]. Previous experimental research had been showed that HEX foam with an expansion ratio of 500:1 had an optimum mitigation effects for LNG fire. Generally, HEX foam made the LNG burning rate reduced in a large amount. Considering of effect of the pool size, the burning rate could be written as [22]

\[
\dot{m}^* = \dot{m}^* - e^{-\kappa \beta D} 
\]

Where \( \dot{m}^* \) is the LNG burning rate (kg/(m²⋅s)); \( \dot{m}^* \) is the maximum time-independent constant burning rate (0.08 kg/(m²⋅s)); \( D \) is the LNG pool diameter; \( \kappa \) is the absorption-extinction coefficient of flame and \( \beta \) is a mean-beam-length correction; \( \kappa \beta \) is equal to 1.1 [m⁻¹] for LNG. For large pool, the wind may cause an increased burning rate. The formula suggested by Blinov and Khudiakov [23] may be applied, i.e.

\[
\frac{\dot{m}^*_{\text{windy}}}{\dot{m}^*_{\text{still}}} = \left(1 + 0.15 \frac{u}{D}ight)
\]

Where \( \dot{m}^*_{\text{windy}} \) and \( \dot{m}^*_{\text{still}} \) are the wind-influencing and no-wind LNG burning rate; \( u \) is the wind velocity. A semi-empirical correlation was assumed to consider the burning rate when LNG pool was covered by HEX foam,

\[
\dot{m}^* = \dot{m}^* - e^{-\kappa \beta D} \left(1 + 0.15 \frac{u}{D}\right) e^{-\frac{\delta \nu \epsilon t}{V}}
\]

\( \delta \) is the HEX foam factor only related with foam expansion ratio; \( \nu \) is the HEX application rate (m³/(m²⋅s)); \( A \) is the opening area of HEX foam generator (m²); \( t \) is the HEX foam working time; \( V \) is the LNG pool volume (m³). HEX foam factor \( \delta \) was the key value for suppression of the burning rate of LNG pool fire. In a higher value \( \delta \), LNG pool fire was suppressed quickly and flame length was minimized in a short time. For foam expansion rate 500: 1, \( \delta \) equaled to 30000 through comparing with Suardin’s experiments. The conditions of the experiments were summarized in Tab. 3. Test 3 and 4A were applied for simulation.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4A</th>
<th>4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool area (m²)</td>
<td>45</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>HEX foam application rate (L/(m²⋅min))</td>
<td>10</td>
<td>3.5</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Radiometer location from pool edge (m)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>Average wind speed (m/s)</td>
<td>3.7</td>
<td>NA</td>
<td>1.2</td>
<td>2.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>15.8</td>
<td>NA</td>
<td>26.7</td>
<td>24.5</td>
<td>28.7</td>
</tr>
</tbody>
</table>
Figure 11. Heat flux vs. time in the 65 m² LNG pool fire with different HEX foam application rate

Figure 12. Evolution of LNG pool fire flame at different burning time

Fig. 11 illustrated the comparison of the predicted value and experimental data of Test 3 and Test 4A, respectively. Fire Control Time (FCT) was defined as the time required for 90% heat flux reduction, as specified in NFPA 11[24]. In the experiment, 90% heat flux reduction arrived at 100s and 60s, comparing of 130s and 55s in the simulation.

The sequence of plots in Fig. 12 demonstrated the pool fire flame changing with time in Test 3. The LNG pool fire started from t=0 s. At t=22 s, the fire was fully developed. Meanwhile, HEX foam was turned on. The fire flame length was declined quickly within 30 s. At t=4 min, the fire reached at a steady-state burning, with a consistent flame length. However, the fire was not extinguished by HEX foam although the time extended as long as 10 min.

5. CONCLUSION

In this study, LNG vapor dispersion and LNG pool fire radiation CFD models were validated through modeling historical field tests. The relative error of CFD model of pool fire radiation was lower than 10%. It concluded that CFD model could describe the complex terrain effectively. The two mitigation methods for LNG hazards, water curtain and HEX form, were studied. CFD simulation indicated that water curtains acted mainly as a porous barrier to block LNG vapor dispersion, which could reduce the hazardous area significantly. The effectiveness of HEX foam depended heavily on the foam expansion ratio and application rate. A new correlation was introduced to calculate the LNG pool fire burning rate. For foam expansion ratio 500:1, the HEX foam factor equaled 30000 through validating the experiments.
REFERENCES


