CFD Simulation on Leakage and Explosion Accident of Liquefied Hydrocarbon Loading Station and Dynamic Responses Analysis of Control Room

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Abstract. Considering the dangerous characteristics of Liquefied hydrocarbon loading station, a three-dimensional model of a certain liquefied hydrocarbon working area was established to simulate the accident of liquefied hydrocarbon leakage and vapour cloud explosion, and the relationship between the number of loading vehicles and explosion overpressure was analyzed. Meanwhile, the existing control room is not designed for anti-explosion, and the personnel are relatively concentrated, so the dynamic response of the control room under explosion loading needs to be analyzed. The researches show that due to the blocking effect of propylene substation on the combustible gas cloud under north wind, the equivalent stoichiometric cloud mass is higher than that in the southwest wind direction. The blocks in the working area are mainly distributed along the east-west direction, so the peak overpressure of the propylene substation is smaller than that of the control room. There is a linear relationship between the loading vehicles and the explosion overpressure in the control room. With the decrease of the number of loading vehicles, the explosion overpressure decreased significantly. If the number of loading vehicles is not reduced, the brick wall of the existing control room will be broken and collapsed under explosion loading, threatening the safety of personnel in the control room.

1. Introduction
In recent years, the construction of petrochemical industry zones has developed rapidly, the production scale of petrochemical enterprises has been continuously expanded, and the transportation of low-temperature hazardous chemicals such as liquefied hydrocarbons by tanker truck has developed quickly [1-3]. After the leakage of liquefied hydrocarbon, the volume will expand rapidly and evaporate into steam rapidly, and interact with the air to form a flammable, explosive and continuously spreading vapor cloud. Once the vapor cloud explosion accident occurs, it may cause massive casualties [4-7]. Moreover, control room is the commander in chief of the whole technological process. It provides centralized control and monitoring to the productive process and it can also act as the stuff’s shelter [8-11].

Therefore, CFD simulation technology is used to simulate the leakage explosion accident of liquefied hydrocarbon loading station. Based on the simulation results of vapour cloud explosion, the finite
element method is used to analyze the dynamic response of the existing control room under explosion load. It is of great significance to put forward effective accident control and mitigation measures for optimizing the layout of tank truck loading area, anti-explosion design of control room, safety monitoring of liquefied hydrocarbon leakage and emergency response.

2. loading zone model
CASD module of FLACS is used to build a full-size three-dimensional physical model of the liquefied hydrocarbon loading zone, as shown in Fig.1. The area mainly includes loading station, parking lot, control room, guard room, propylene substation, and surrounding residential buildings.

![Figure 1. Liquefied hydrocarbon loading zone.](image)

3. leakage and diffusion of liquefied hydrocarbon

3.1. Diffusion Simulation Scene

| Leakage location | Leaking substance | P/M Pa | T/°C | Leakage Diameter/mm | Leakage Rate/(kg/s) | Wind Direction | Leakage Time/min |
|------------------|------------------|--------|------|---------------------|---------------------|----------------|-----------------|
| loading arm      | propane          | 2      | 30   | 50                  | 59.72               | SW             | 1               |
|                  |                  |        |      |                     |                     |                | 3               |
|                  |                  |        |      |                     |                     |                | 10              |
| loading arm      | propane          | 2      | 30   | 50                  | 59.72               | N              | 1               |
|                  |                  |        |      |                     |                     |                | 3               |
|                  |                  |        |      |                     |                     |                | 10              |

In view of the dangerous characteristics of the liquefied hydrocarbon working area [12-13], It is assumed that the connection between loading arm and liquid phase pipe of tank truck is not reliably connected, leading to liquefied gas leakage accident. The crane pipe diameter (DN50) was used as the leakage diameter, and propane was used as the simulation substance. According to the FLASH module of FLACS, the leakage rate of liquefied hydrocarbon is 59.72kg/s. The parameters of leakage simulation is shown in Table 1.

3.2. Leakage Diffusion Results and Analysis

The most dangerous situation of a leakage accident is the formation of liquid pools on the ground after the leakage of liquid hydrocarbons, and then the liquid pool evaporates to form flammable vapor cloud, which diffuses into the surrounding environment and explodes in case of fire. The diffusion range of 1/4 LFL cloud with different leakage times is shown in Fig.2.
The maximum equivalent stoichiometric cloud (Q9) and the farthest diffusion distance of 1/4 LFL cloud in different accident scenarios are shown in Fig.3 and Fig.4, respectively. Both of them are larger in the north wind than in the southwest wind under the same conditions, and the difference between them increases with the increase of leakage time.

The reason is that the diffusion of gas cloud is not only related to wind speed, but also affected by the layout of buildings, equipment and facilities. As shown in Fig.2, the blocking effect of propylene substation on the combustible gas cloud under the north wind direction leads to the gas cloud clustering around the substation, resulting in higher Q9 than the diffusion in the southwest wind direction. When the cloud bypasses the substation, there are fewer barriers, so its diffusion distance is also far.

Figure 2. Diffusion range of 1/4 LFL cloud.
4. liquefied hydrocarbon vapor cloud explosion

4.1. Explosion Simulation Scene

According to the simulation results of leakage and diffusion, a large number of liquefied hydrocarbons leak and gasify sharply after the interface of loading arm is detached, and the loading platform is completely surrounded by flammable gas cloud. Therefore, it is assumed that gas cloud covers the entire loading station, the concentration of the gas cloud is the chemical equivalent ratio, and the ignition source is located at the edge or center of the gas cloud.

4.2. Explosion Results and Analysis

When the center of gas cloud is ignited, the propagation process of blast wave is shown in Fig.5 and Fig.6.

The statistics of peak overpressure in different areas of the loading platform under different ignition conditions are shown in Table 2. It can be seen from the table that the peak overvoltage at the control room is 13.3 kPa and that at the propylene substation is 9.5 kPa. The propylene substation is closer to the explosion source, but the blockage is mainly distributed along the east-west direction, so its peak overpressure is lower than that of the control room. The peak overpressure at loading station fence is 21.1 kPa. The existing masonry wall may collapse. It is suggested to transform loading station fence into reinforced concrete anti-explosion wall to enhance its own anti-explosion ability, avoid the collapse of the wall and the injury caused by debris. It can also shelter the control room behind the wall. The peak overpressure of residential buildings is small, which is not enough to cause serious damage.
Figure 6. Blast wave propagate to Residential buildings

Table 2. Statistics of peak overpressure

| Area                      | Peak Overpressure /kPa |
|---------------------------|------------------------|
| control room              | 13.3                   |
| loading station fence     | 21.1                   |
| propylene substation      | 9.5                    |
| residential building      | 5.6                    |
| parking lot               | 7.3                    |

4.3. Relationship between Loading Vehicles and Overpressure
The explosion accidents of liquefied hydrocarbon vapor cloud were simulated when different number of tankers were loaded at the same time. Gas cloud covers all vehicles, the concentration of the gas cloud is the chemical equivalent ratio, and the ignition source is located at the center of the gas cloud.

Figure 7. The relationship curve between the number of loading vehicles and overpressure.

The relationship curve between the number of loading vehicles and explosion overpressure is shown in Fig.7. From the graph, it can be seen that there is a linear relationship between the number of loading vehicles and explosion overpressure. With the decrease of the number of loading vehicles, the explosion overpressure in the control room decreases significantly, from 13.3 kPa (8 vehicles) to 2.3 kPa (2 vehicles). Therefore, reducing the number of loading vehicles can mitigate the severity of explosion consequences.
5. DYNAMIC RESPONSE OF CONTROL ROOM
The peak overpressure at the control room is 13.3 kPa and the positive pressure time is 197.5 ms. there is a risk of wall collapse in the explosion accident. Therefore, a single wall model of the control room is established to simulate the dynamic response of the wall under explosive load.

5.1. Front Wall Loading
The blast load acting on the front wall of a closed rectangular building can be calculated by the following formula [14-15]:

Peak reflected pressure:

$$P_r = \left(2 + 0.0073P_{so}\right) \bullet P_{so}$$  \hspace{1cm} (1)

Where: $P_r$—Peak Reflected Pressure (kPa)

Stagnation pressure:

$$P_s = P_{so} + C_d \bullet q_o$$  \hspace{1cm} (2)

Where: $P_s$—stagnation pressure (kPa)

$C_d$—drag coefficient, the drag coefficient depends on the shape and orientation of the obstructing surface. For a rectangular building, the drag coefficient may be taken as +1.0 for the front wall, and -0.4 for the side and rear walls, and roof.

The duration of the equivalent triangle:

$$t_c = 3S/U < t_d$$  \hspace{1cm} (3)

$$t_e = 2I_s/P_r = \left(t_d - t_c\right) \bullet P_s/P_r + t_c$$  \hspace{1cm} (4)

$$I_s = 0.5 \bullet \left(P_r - P_s\right) \bullet t_c + 0.5 \bullet P_s \bullet t_d$$  \hspace{1cm} (5)

Where: $I_s$—Positive pressure impulse

$S$—clearing distance, the smaller of H or B/2(m)

$t_c$—The duration of the equivalent triangle (s)

$t_e$—the duration of the reflected overpressure effect (s)

According to the above calculation, front wall loading is shown in Fig.8
5.2. Single Wall Model and Material Parameters
According to the architectural drawings, the front wall size is 4000×4000×240mm. SolidWorks is used for modeling of the brick wall, and ANSYS ls-dyna is used for finite element analysis. The wall is composed of M15 clay sintered brick and M5.0 mixed mortar. The volume of the brick is 240×115×53mm, the mortar thickness is 10mm, the bricks and mortar adopt the joint connection mode, the single wall model is shown in Fig.9.

![Figure 9. Single wall model.](image)

5.3. Wall Dynamic Response
Fig.10 shows the deformation of the brick wall at different times (100ms, 200ms, 300ms, and 650ms) under explosion load. It can be seen that the brick wall will be broken and collapsed.

![Figure 10. Deformation of the brick wall.](image)
The brick at the center of the wall is selected for analysis. The relationship curves of brick velocity, kinetic energy and time are shown in Fig.11 and Fig.12 respectively. It can be seen that in the period of 0-100ms, no obvious displacement of the bricks occurs due to the vibration and energy absorption of the wall itself. However, with the increase of explosive loading time, mortar failure occurs. When the mortar around the brick fails, the brick loses bond and starts to fly out. The velocity and kinetic energy of the brick increase significantly.

6. Conclusion

(1) Due to the blocking effect of propylene substation on the combustible gas cloud under north wind, the equivalent stoichiometric cloud mass is higher than that in the southwest wind.

(2) Propylene substation is closer to the explosion source, but the blocks in the working area are mainly distributed along the east-west direction, so the peak overpressure of propylene substation is lower.

(3) There is a linear relationship between the loading vehicles and the explosion overpressure in the control room. With the decrease of the number of loading vehicles, the explosion overpressure in the control room decreased significantly. Reducing the number of loading vehicles can mitigate the severity of explosion consequences of liquefied hydrocarbon vapor cloud.
(4) The peak overpressure at loading platform fence is 21.1kPa. The existing masonry wall may collapse. It is suggested to transform loading platform fence into reinforced concrete anti-explosion wall to enhance its own anti-explosion ability, avoid the collapse of the wall and the injury caused by debris.

(5) If the number of loading vehicles is not reduced, the brick wall of the existing control room will be broken and collapsed under explosion loading, threatening the safety of personnel in the room. It is suggested to reinforce the control room to ensure the integrity of the brick wall in explosion accident.

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