Simulation of LPG tank truck leakage and explosion accident based on CFD

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Abstract. Road transportation of hazardous chemicals has a high risk and is likely to cause serious road traffic accidents. In this paper, the most common LPG tanker in hazardous chemical transportation is taken as the research object. Based on the CFD method, we used FLACS software to simulate LPG tank car accident in Italy. The leakage process of LPG tank car after leakage was simulated, and the diffusion process of propane and butane mixture in one minute when the accident occurred. It was further analyzed that the leakage material exploded when it encountered the ignition source, and the shock wave overpressure was the highest at 2.5 seconds after the explosion, with the shock wave pressure exceeded 0.26MPa. Also, the attenuation of the blast wave is higher in the area far away from the explosion source. The research results can provide effective data support for on-site emergency disposal and personnel evacuation of similar accidents.

1. Introduction
With the rapid development of China’s economy, China’s petroleum and chemical products present more categories, large output and frequent transportation. According to the data statistics in 2019, the added value of China’s petroleum and chemical industry increased by 4.8% over the previous year, and the operating income was 12.27 trillion yuan, up by 1.3%, accounting for 12.4% of the national GDP and 40% of the global chemical output value, ranking first in the world. China’s annual road transportation of hazardous chemicals is close to 1.6 billion tons, accounting for more than 30% of the total annual freight volume. In 2019, China’s hazardous chemicals logistics market exceeded 1.8 trillion yuan. There are more than 11,500 hazardous chemicals road transport enterprises nationwide, employing more than 1.2 million people and more than 300,000 transport vehicles.

According to the Ministry of Emergency Management statistics, there were two tragic accidents resulting in 20 deaths in the transportation of hazardous chemicals in China in 2017. In 2018, two serious accidents of hazardous chemicals lead to 43 deaths. From January to August in 2019, a total of 103 people died in dangerous chemicals traffic accidents. The data show that the frequency of hazardous chemical accidents on-road transportation in China is getting higher and higher, and the number of deaths is also increasing gradually. Therefore, road transportation of hazardous chemicals has a greater safety risk, which will cause casualties and have a negative impact on social stability.

Liquefied Petroleum Gas (LPG) is a kind of flammable, explosive and toxic gas that is easy to cause serious combustion, explosion and poisoning accidents after it leaks. Jin Xin[1] used the CFD simulation method to simulate LPG leakage and used the particle walking model to simulate and analyze the LPG leakage process. Zhai Meiyu, Ma Guiyang, et al.[2] used the CFD method to simulate the influence of leakage shape on LPG leakage and diffusion. It was found that the triangle orifice had...
the largest risk area of leakage and diffusion, followed by the circular orifice, and the square orifice had the smallest influence. Liu Yujin, Tan Wei, Liu Liyan, et al.[3] used the CFD method to analyze the diffusion and characteristics of two-phase cloud clusters produced by LPG leakage under different wind speeds.

2. Research method

CFD (Computational Fluid Dynamics) is a subject composed of fluid mechanics, mathematics and computer science and is established on the basis of fluid dynamics and numerical calculation methods[4,5]. It mainly studies the heat, mass and momentum transfer in the process of fluid flow, material combustion and chemical reaction, and multiphase flow [6]. Starting from the basic physical theorem, CFD has largely replaced the expensive experimental equipment of fluid dynamics, which has a great impact on scientific research and engineering technology.

FLACS software is a simulation software developed by GexCon company based on CFD technology. The software’s models for the diffusion, fire and explosion of hazardous chemicals have been verified by full-scale experiments. It has been certified by international authoritative standards such as the United States, Norway and Russia, and has a wide range of applications in high-risk fields such as petroleum, chemical and natural gas. Based on the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) method[7], FLACS software established the conservation equations of mass, momentum, energy and composition to describe fluid characteristics using the finite volume method. With boundary conditions, the values of overpressure, combustion products, flame velocity and fuel consumption are calculated[8]. As shown in the formula below, the effects of turbulence and chemical reaction are also included in the equations.

\[
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x_j} (\mu_x \rho \phi) - \frac{\partial}{\partial x_j} \left[ \rho \Gamma \frac{\partial}{\partial x_j} (\phi) \right] = S_{\phi}
\]

In the formula, \(\phi\) represents the general solution variables (including mass, momentum, energy, etc.), \(\rho\) is the gas density, \(x_j\) is the integral in the \(j\) direction, \(\mu_x\) represents the velocity vector in the \(i\) direction, \(\Gamma\) is diffusion coefficient, \(S_{\phi}\) is the solution results. This method takes into account the interaction and influence of the flame with devices, pipelines, equipment, etc., and can directly calculate the gas explosion shock wave.

In general, two explosion accidents may occur after oil leakage occurs in LPG tank car due to collision rollover[9,10]. In the first case, it often explodes within a few minutes after a tank truck catches fire, leading to further expansion of the consequences of the accident[11]. In the second case, a liquid pool is formed on the ground to expand, evaporate and form a combustible gas cloud after the fuel leaks[12]. The combustible gas cloud explodes when it encounters a fire source during the spreading process, which the fuel energy released rapidly. This explosion has a greater destructive power and a greater range of damage, which is our case study in this paper.

3. Simulation of tank car leakage and explosion accident

On August 6th, 2018, an LPG tanker collided with a truck on the highway bridge section from Bologna to the airport and the resulting flame was generated. Four minutes later, a devastating explosion caused the road bridge to collapse. The accident caused two people to die on the spot, more than 145 people were injured, and the surrounding vehicles and buildings were extensively damaged. According to the actual situation on the day of the accident in Bologna, Italy, we set up an accident simulation scenario to simulate the process of the accident. The numerical simulation modelling process is carried out in the FLACS modelling module CASD.

3.1. FLACS simulation parameters

After collecting accident scene data, we know that the tanker that caused the rear-end collision carried 30,000 liters of LPG. Therefore, the distances of the entire simulation calculation area in the \(xyz\) direction are 200 m, 60 m, and 30 m, respectively. The accident occurred on August 6th, Italian time. At that time, the ambient temperature was 28°C, the atmospheric pressure was normal, and the
atmospheric stability was Class D, without the impact of severe environmental wind speeds. The tanker in the accident was fully loaded with LPG, with a total length of 14 m and a width of 2.5 m. The maximum pressure in the tank is 2.2 MPa, and the leak occurs at the safety valve on the upper part of the tank. The fire source that detonated the LPG tanker was a typical open flame caused by the combustion after the accident. The specific parameter settings are shown in Table 1.

### Table 1. Parameter setting of FLACS numerical simulation

| Parameter type                      | Set value                     |
|------------------------------------|-------------------------------|
| Calculation range (X,Y,Z)          | 200×60×30 m                   |
| Tank size                          | Tank length 14 m, Tank width 2.5 m |
| Fuel type                          | liquefied petroleum gas       |
| Tank pressure                      | 2.2 MPa                       |
| Leak location                      | At the safety valve above the tank |
| Types of ignition sources          | Open flame                    |
| Atmospheric pressure               | 0.1 MPa                       |
| Ambient temperature                | 28 ℃                          |
| Monitoring point type              | Speed, pressure, temperature  |

#### 3.2. LPG diffusion process

According to the scene surveillance video of the LPG tanker accident in Bologna, this study simulated the LPG leakage process within 1 minute after the LPG tanker collided. After the LPG tanker leaked, the high-pressure medium inside the tank leaked out from the safety valve on the top of the tank. LPG is mainly a mixture of propane and butane with a small amount of propylene and butene. Therefore, when the mixture leaks from the small hole of the high-pressure vessel, it will diffuse around the leakage source in the form of heavy gas diffusion. After the accident simulation calculation in the FLACS software, the leakage process of the LPG tanker is shown in Figure 1.
3.3. LPG tanker explosion process

According to the image data on the day of the accident, the LPG tank car exploded for about 3 seconds. The explosion formed a huge fireball which dissipated immediately after taking off, transferred strong heat radiation to the surrounding and caused the steel surface of the car near the parking to melt. The LPG explosion process is simulated in FLACS software and is showed in Figure 2.
4. Simulation result analysis

Figure 3 shows the process of shock wave of LPG tanker. According to the overpressure of explosion shock wave obtained by FLACS numerical simulation, it can be seen that the explosion shock wave first increases and then decreases rapidly with the explosion time. The pressure rise rate is the highest at the beginning of explosion and then gradually decreases. The shock wave overpressure caused by the LPG tank truck explosion is the highest in 2.5 seconds after the explosion, and the shock wave pressure is more than 0.26 MPa, which will cause fatal damage to the surrounding personnel and cause devastating damage to the surrounding buildings. The explosion shock wave has a high attenuation degree in the far-field of the explosion source, which will cause different levels of damage to the glass windows and other enclosure structures in the area.

Figure 4 shows the flame propagation changes after the explosion of the LPG tanker. As shown in the figure, a certain scale of fire started to form at the scene of the accident after the explosion. With the impact of the explosion shock wave, the flame speed increases rapidly and reaches the highest point in about 5 seconds, and the flame propagation speed began to slow down as the LPG tanker explosion ended instantly.
Figure 4. The flame propagation changes after the explosion of the LPG tanker

Figure 5 shows the fuel changes inside the tank of the LPG tanker. The curve shows that the LPG content in the tank decreases rapidly in the process of leakage accident and explosion. In the figure, we can clearly see that 6 seconds later, when the explosion is over, the fuel inside the tank is almost exhausted.

Figure 5. The fuel changes inside the tank of the LPG tanker

5. Conclusion
There are many types of hazardous chemicals in transportation, and the vehicles transported have different standards. The study on the leakage and explosion accidents of LPG tankers is representative. With the help of simulation software, it is possible to better realize the numerical simulation analysis of leakage and diffusion, reverse the accident process, and get the numerical parameters of the accident process. These are of great significance for studying the destructiveness of accidents and formulating relevant emergency strategies in time.

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