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SIMULATION ON THE DISPERSION OF NATURAL GAS AND ITS VOLUME CLOUD DISTRIBUTION ON AN OFFSHORE FIXED PLATFORM

The formation, migration and volume distribution of gas clouds, which are dominated by natural gas after oil and gas leakage, are the material basis of fire and explosion accidents on offshore platforms. Based on an offshore platform as the background, this paper conducts research on the gas cloud using numerical simulation method, the selection of different wind speeds, leak leakage rate of quality, wind direction and the direction angle, the leakage of gas diffusion behaviour simulation studies and its size distribution. There is a "coupling" effect on the volume value of 5% CH_4 cloud between different wind speeds, leakage mass rates, and wind direction and leakage direction. When the wind speed is 13 m/s, the leakage mass velocity is 8 kg/s, and the included angle between wind direction and leakage direction is 180°, the "coupling" effect on the volume value of 5% CH_4 cloud increases significantly. The above research results can provide a reference for the reasonable division of process risk area, firewall design and quantitative risk assessment of fire and explosion of an offshore platform.

Keywords: Offshore platform safety; Gas explosion prevention; Gas leakage dispersion; Gas cloud distribution; Gas leakage simulation

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Introduction

At present, there are more than 250 fixed offshore platforms (hereinafter referred to as offshore platforms) around China's seas, which are the main equipment for the development of offshore oil and gas fields. Fire & explosion are one of the most serious accident types during the development of offshore platform oil and gas. According to relevant accident statistics, more than 70% of offshore platform safety accidents originate from oil and gas leaks and fire/explosion. For example, in April 2010, the Macondo oil and gas leak on BP's "Deep Water Horizon" oil drilling platform located in the United States Gulf of Mexico caused a fire and explosion, which sank the platform, and 11 people died [1]. The formation of natural gas-based combustible gas clouds after oil and gas leakage is the material basis of fire and explosion accidents on offshore platforms. Its formation, migration and volume distribution have an important impact on the occurrence of fire and explosion accidents. A large number of researches on the leakage and diffusion of combustible gas have focused on the LNG and LPG leakage and diffusion problems, which were stored by various devices like tanks, trucks, and receiving terminals on land [2-6]. On the one hand, LPG and LNG have the characteristics of heavy gas, and their leakage and diffusion behaviours are very different from those of natural gas. On the other hand, the dispersion and distribution behaviours of natural gas are quite different between offshore platforms and storage tanks, due to the influential factors such as location, leakage and environment. Although some scholars have carried out studies on the natural gas leakage and diffusion behaviour of floating production facilities represented by FPSO (Floating Production Storage and Offloading) and semi-submersible platforms (also known as column stabilised drilling platform), there are relatively few studies of fixed offshore platform. The type and layout of equipment and facilities are very different from each other. Furthermore, research mainly focuses on natural gas leakage under blowout conditions, which are significantly different from the natural gas leakage conditions on offshore platforms [7-10]. Researchers now focus on conducting studies on the quantitative risk analysis (QRA) [11-13], which is applied to evaluate the risk level of offshore facility production. While the dispersion and distribution of natural gas clouds are regarded as the inputs of QRA calculations. Therefore, this paper carried out the study on natural gas dispersion behaviour and gas cloud distribution, influenced by key factors such as wind speed, wind direction, leakage rate, and leakage direction, via taking the fixed offshore platform.

1. Dispersion theory

The software used for CFD simulation in this paper is KFX, developed by DNV, and its calculation principle is based on the three-dimensional compressible unsteady Navier-Stokes equation as the governing equation. The concentration distribution and diffusion process of CH_4 appear as a complex, unsteady turbulent flow that follows the conservation of mass, momentum, and energy. The differential equation controlling the flow field is expressed in a general form as formula (1):

$$\frac{\partial}{\partial t}(\rho\varphi)+div(\rho u\varphi)=div(\Gamma grad\varphi)+S_{\varphi} \tag{1}$$

where:

ρ – fluid density;

φ – a general variable, including variables such as mass, momentum, energy and turbulent energy;
u – velocity;
Γ – the diffusion coefficient;
S_φ – the source term.

The standard κ-ε turbulence model is based on Reynolds' equations of averages, which decompose the fluid into the mean flow and turbulent parts, where the mean flow part consists of the mean velocity, pressure, and temperature, and the turbulent part consists of the turbulent velocity, pressure, and temperature. The standard κ-ε turbulence model is suitable for flow problems with medium to high Reynolds numbers, where the Reynolds number is mainly affected by the ratio of inertial and viscous forces. The standard κ-ε turbulence model is used to describe it, and the turbulent transport equation is formula (2) and (3) [10]:

$$\frac{\partial}{\partial t}(\rho\kappa)+\frac{\partial}{\partial x_i}(\rho\kappa u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial x_j}\right]+ \\ +G_\kappa+G_b-\rho\varepsilon-Y_M+S_\kappa \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+ \\ +C_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_\kappa+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa}+S_\varepsilon \tag{3}$$

Where:
μ – the hydrodynamic viscosity, N·s/m^2;
μ_t – the vortex viscosity of the fluid, N/m^2;
u_i – the i-th direction component of the fluid velocity, m/s;
κ – the turbulent flow energy, m^2/s^2;
ε – the turbulent energy dissipation rate, W/m^3;
σ_κ and σ_ε – the turbulent Prandtl numbers of κ and ε, taking 1.0 and 1.3, respectively;
G_κ and G_b – the influence of the average velocity gradient and buoyancy on the turbulent kinetic energy respectively;
Y_M – the contribution of the fluctuation expansion of compressible turbulence to the overall dissipation rate;
$C_{1\varepsilon}$ and $C_{2\varepsilon}$ – constants, taking 1.44 and 1.92, respectively;
$C_{3\varepsilon}$ – the influence of buoyancy on the turbulent dissipation rate;
S_κ and S_ε – user-defined source terms.

2. Fixed platform

2.1. Geo-model of platform

This article takes the typical offshore fixed platform as the engineering background. The fixed platform, equipped with 8-leg pile groups, includes 3 layers, upper deck, middle deck and lower deck, from top to bottom. In addition, it also contains the mezzanine deck and cable walkways. In this paper, the author selects the lower deck as the leakage point, which includes the process danger zone and the safety zone, separated by the explosion-proof wall. The process area consists of a wellhead area, a TEG regeneration skid, an oil-gas-water three-phase separator, and other skid-mounted production equipment and facilities. The safety zone mainly consists of a crude oil generator room, storage room, working room, control room, instrument tank, etc. The physical model of the offshore platform and the layout of equipment and facilities on the deck where the leak is located are shown in Fig. 1 below.

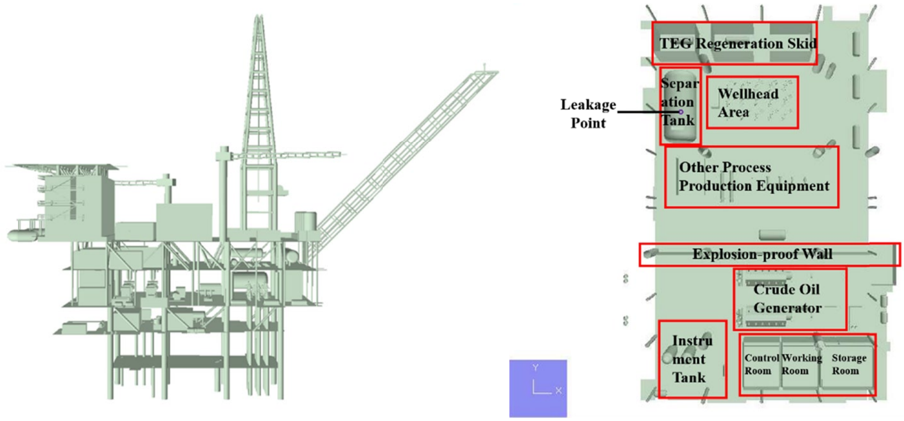


Fig. 1. The geometric model and deck layout of the offshore platform

2.2. Leakage parameters

(1) Determination of leakage parameter

The quality rate of natural gas leakage is mainly affected by many factors such as pressure, temperature, leakage hole size and shape. In this paper, the separation tank is selected as the leakage source, and the certain position on the top of the tank is the leakage point. Three groups of leakage parameters are selected for simulation. The specific leakage working condition parameters are shown in TABLE 1.

TABLE 1

Leakage parameters for simulation

Group	Natural gas component	Leakage mass rate /(kg·s^{-1})	Diameter of hole /m	Temperature /°C	Leak pressure /MPa
1	CH_4: 88%; C_2: 4%; C_3: 3%; CO_2: 5%	3	0.04	70	4.0
2		8	0.06	70	4.0
3		20	0.08	70	4.0

(2) Determination of wind speed and direction

The wind speed of the offshore platform is mainly determined by the meteorological conditions in the sea area. According to the meteorological observation results in the sea area: the main wind direction of the platform is NE, the common wind speed range is 5.0-9.0 m/s, the average wind speed is 7 m/s, and the highest wind speed is 13.0 m/s. The three wind speed values selected in this simulation are 1.0 m/s, 7.0 m/s, and 13.0 m/s. Among them, 1.0 m/s is approximately regarded as the breeze condition and used as the comparative operating condition for leakage and diffusion simulation.

(3) The angle between the leakage direction and the wind direction

The natural gas leakage dispersion law and concentration distribution area are related to the leakage direction. After leakage, natural gas has a certain initial momentum, so the direction of leakage determines the initial velocity direction and initial movement path of natural gas. When the initial velocity of the leaked natural gas gradually decreases to zero, its movement path is the vector sum of velocity and wind speed, which has substantial influence on the diffusion area and concentration distribution of the leaked natural gas cloud cluster within the platform. Based on the most frequent wind direction of the platform, this paper selects the angle between the leakage direction and the wind direction (in the X-Y plane) to be 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°. The simulation is shown in Fig. 2 below.

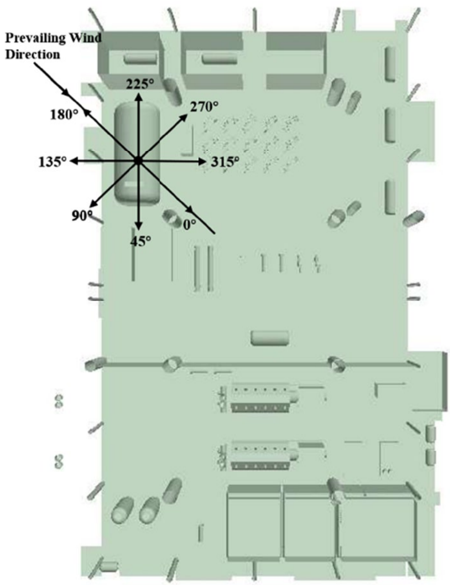


Fig. 2. The diagram of the Angle relation between leakage direction and wind direction

2.3. Simulation panel in KFX

The geo-model of the fixed platform was created in the SCDM module of the ANASYS and saved with a file.obj format. And the file.obj was read into FKX and transferred into the file. kfx. The grid nodes are 516600(84 * 82 * 75). In the format, the geo-model of the fixed platform could be applied for the simulation, as shown in Fig. 3.

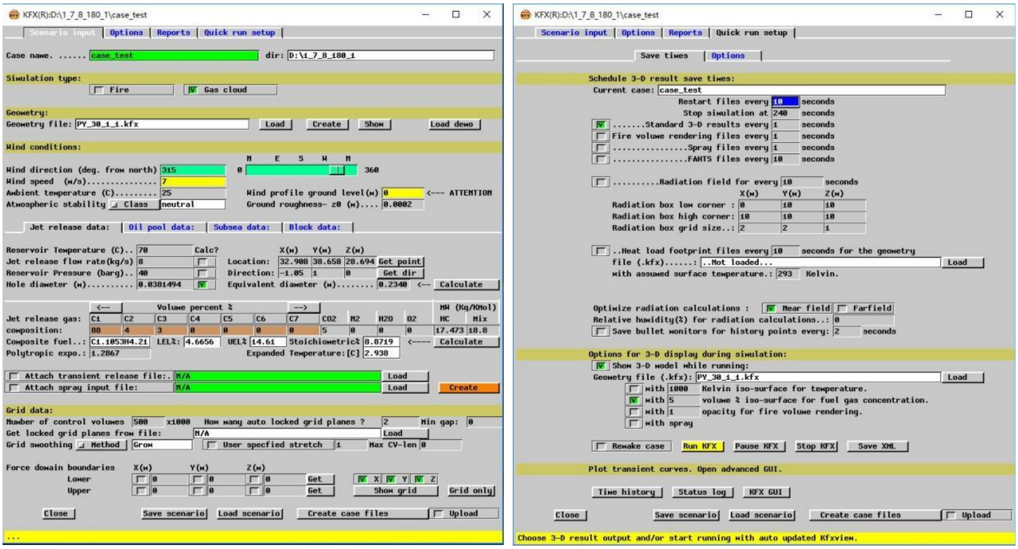
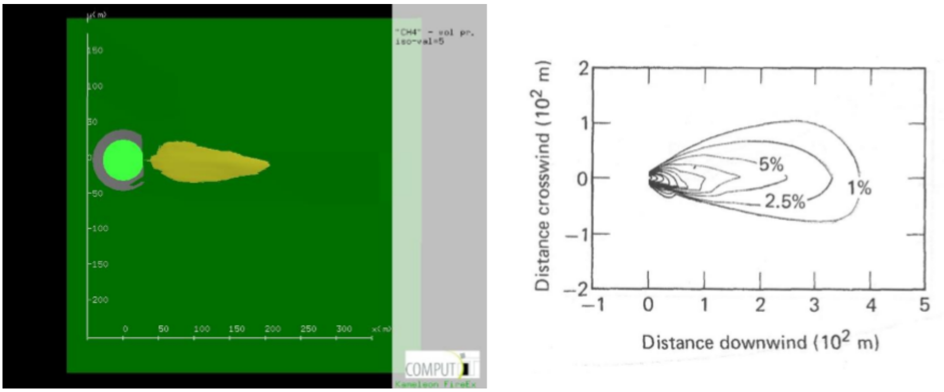


Fig. 3. The simulation panel of KFX

2.3. Verification

The handbook of KFX software describes the accuracy of simulation results by taking the example of the Burro Tests. By comparing the test result and simulation result by KFX, it can demonstrate the good performance in simulating the gas dispersion, as shown in Fig. 4.



(a) 5%CH_4 volumetric concentration contour line (b) methane volumetric concentration contour line

Fig. 4. Comparison of KFX simulation result and Burro test results

As we can see from the two pictures, the shape and area of 5% volumetric concentration of CH_4 between the simulation and tests are highly similar. We could conclude that KFX software could be used to simulate the gas dispersion behaviour.

3. Analysis of simulation results

3.1. CH_4 Dispersion behaviour analysis

3.1.1. CH_4 Concentration distribution in different seconds

When the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angle between the leakage direction and the wind direction is 0°, the CH_4 concentration distribution (Z = 32.5 m profile) at different times is shown in Fig. 5 below.

As can be seen from Fig. 3, with the leakage time increasing, the area covered by the 5% CH_4 cloud cluster becomes larger and larger. In the early stage of the leakage (5 s before), the con-

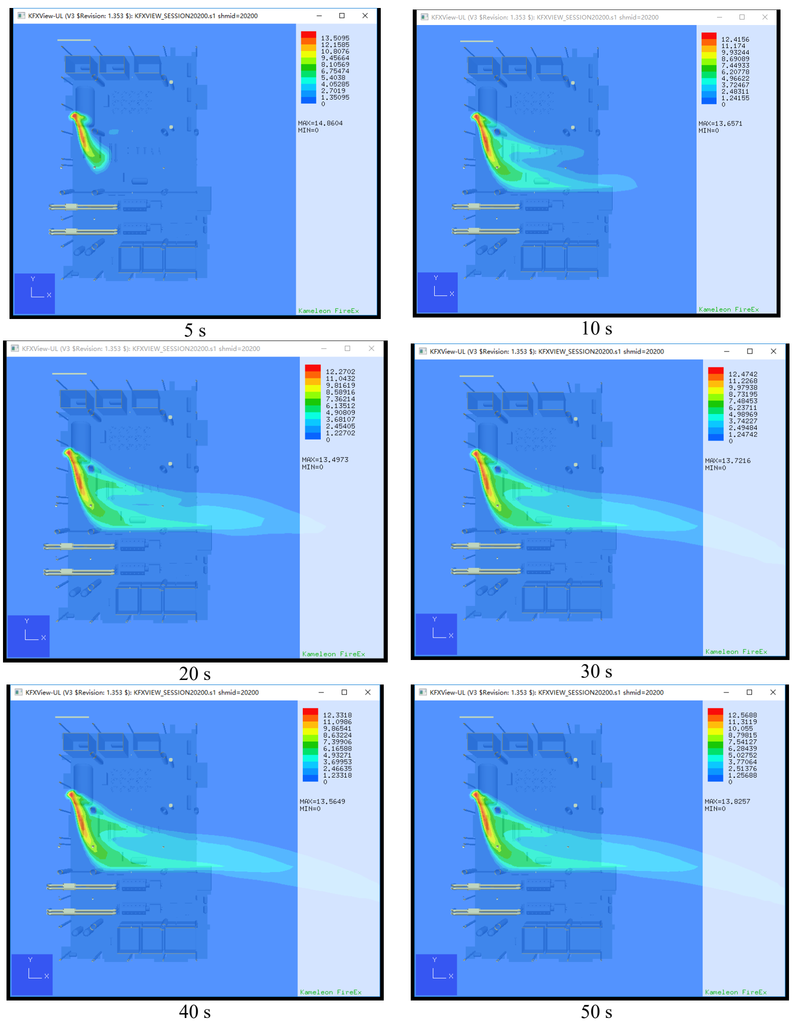
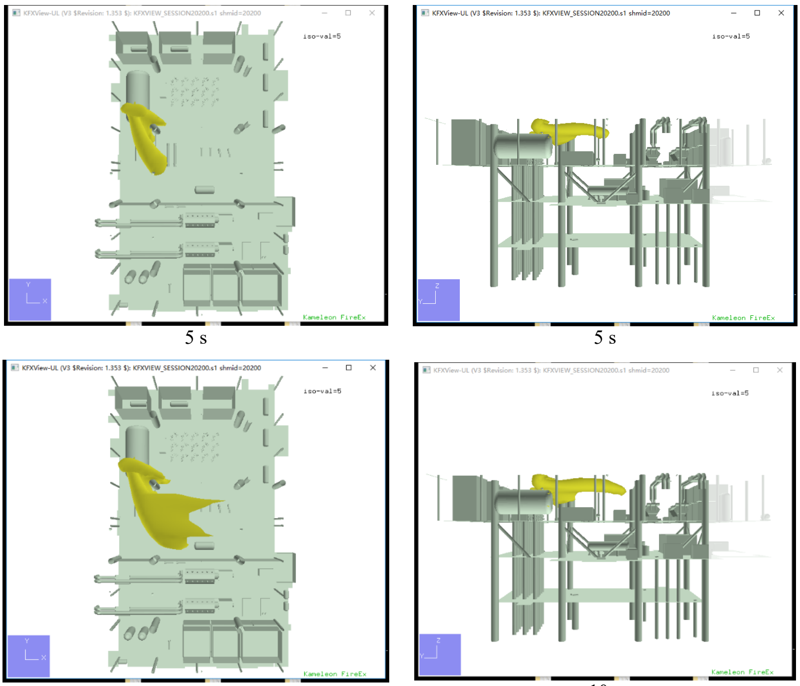


Fig. 5. The concentration distribution of CH_4 in platform profile at different times

centration distribution of CH_4 is mainly affected by the wind flow in the main wind direction and moved along the wind flow direction. But with the leakage time increasing (after 10 s), the movement of CH_4 is deflected by the blocking effect of wind current and explosion-proof wall, and its concentration distribution shape also changes. It can be seen that the arrangement of the explosion-proof wall on the platform can effectively block the diffusion of leaking natural gas, and reduce its diffusion area and the consequences of explosion after leakage. When the leakage time is 30 s, the diffusion concentration coverage area of CH_4 remains basically stable, and its coverage area distribution on the platform deck reaches the maximum, accounting for about half of the area of the deck process area. It can be seen from the concentration distribution of CH_4 profiles at different times in Fig. 3 that the CH_4 cloud cluster has a core concentration area and a peripheral area. The CH_4 concentration in the core concentration area is always above 10%, and its area and distribution shape remained basically unchanged after 5 s. The concentration in the peripheral area is less than 10%, and with the leakage time increasing, the coverage area gradually increases. The increase in the coverage of CH_4 cloud clusters is mainly due to the increase in the coverage of the outer area, which is caused by the diffusion and dilution of CH_4 in this area due to the interaction of wind.

3.1.2. CH_4 Volume distribution in different seconds

When the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angle between the leakage direction and the wind direction is 0°, the distribution of the 5% CH_4 cloud cluster volume with the leakage time (section Z = 34 m, X = 21.5 m), as shown in Fig. 6 below.



5 s 5 s

10 s 10 s

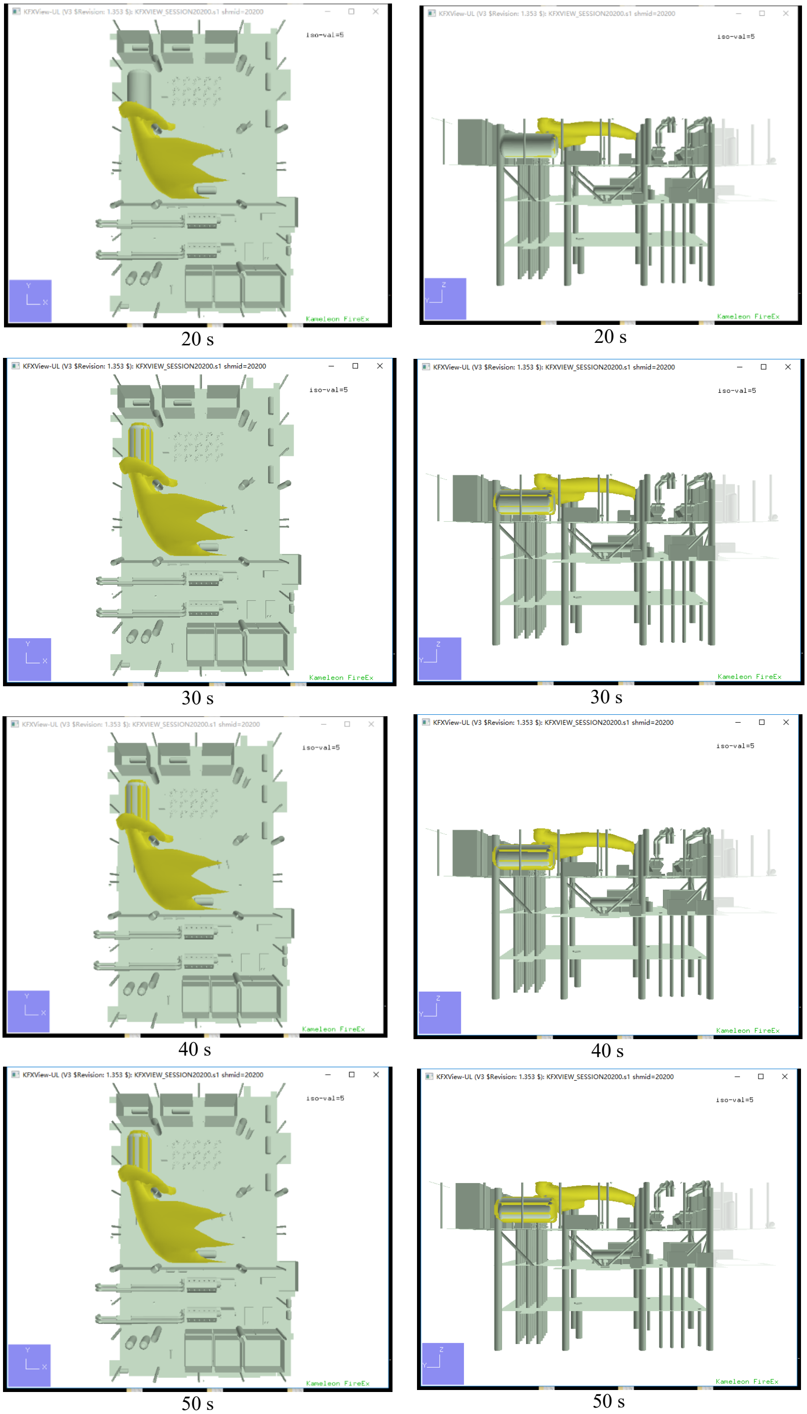


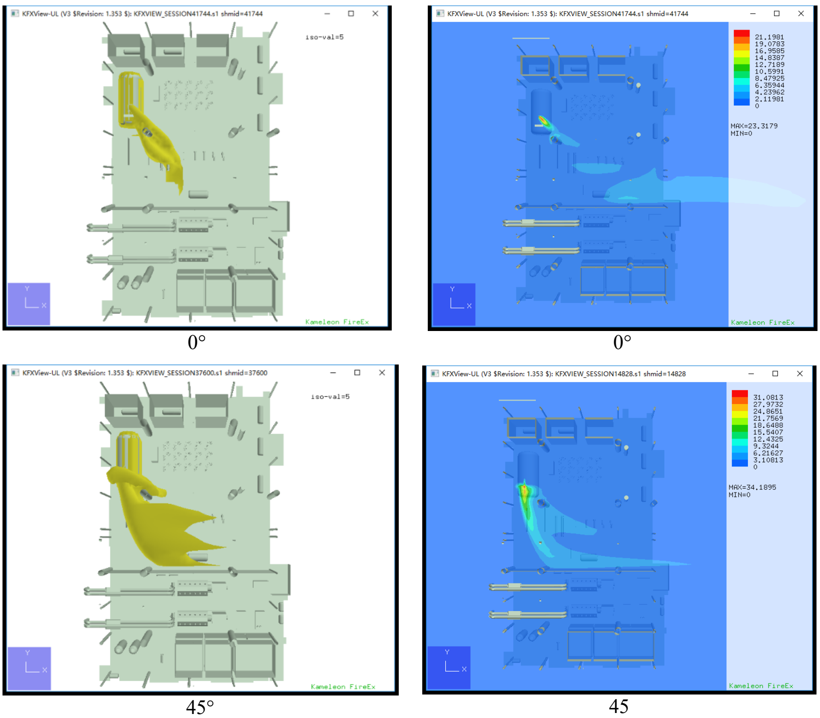
Fig. 6. The spatial and temporal distribution of 5% CH_4 cloud volume on the platform

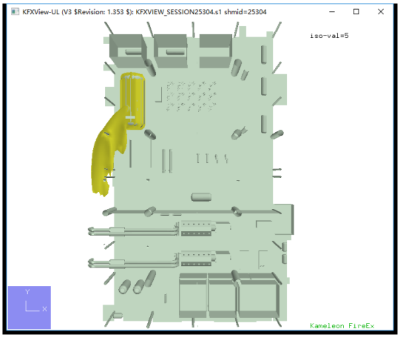
From Fig. 6, it can be seen that under the action of the sea breeze, the volume of the 5% CH_4 cloud continues to expand in the horizontal and vertical directions. The cloud group reaches the explosion-proof wall in 20 s. Under the combined action of wind current and the obstacle of the explosion-proof wall, the cloud group "turns" and moves along the wall of the explosion-proof wall. By comparing the cross-sectional view of the cloud cover area and the top view of cloud volume in Fig. 5, the migration of the CH_4 cloud shows good consistency. When the leakage time is 30 s, the volume of the 5% CH_4 cloud reaches the stable form. At the front end of the movement of the 5% CH_4 cloud, there is an obvious bifurcation phenomenon, which is mainly due to the outcome of the CH_4 cloud encountering vertical pipelines and tanks during the movement, and the result is further aggravated. The arrangement and distribution of pipelines and other equipment on the platform have a significant influence on the migration, shape and volume of the CH_4 cloud.

3.1.3. CH_4 volume distribution at different angles between leakage direction and wind direction

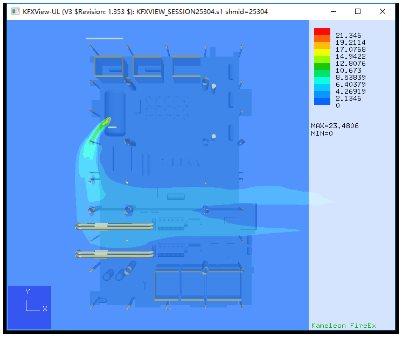
When the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angle between the leakage direction and the direction is 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°. The volume distribution of the 5% CH_4 cloud cluster (section Z = 31.5 m) is shown in Fig. 7 below.

As shown in Fig. 7, the volume distribution of the 5% CH_4 cloud cluster has obvious directional characteristics for different leakage directions, and the wind direction also affects the diffusion behaviour and concentration distribution of CH_4. It can be observed that the final

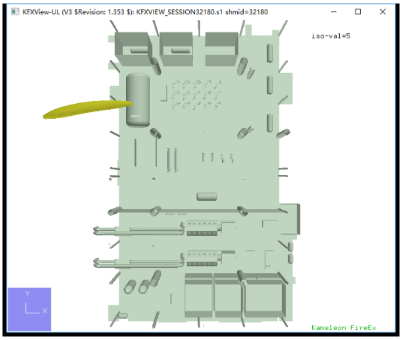




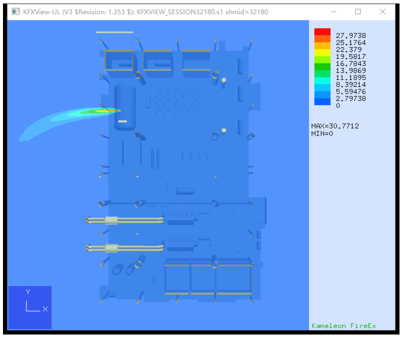
90°



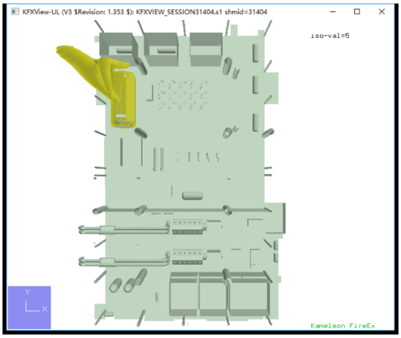
90°



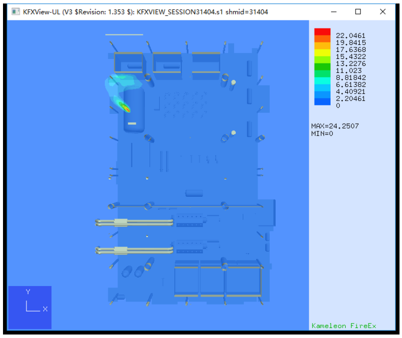
135°



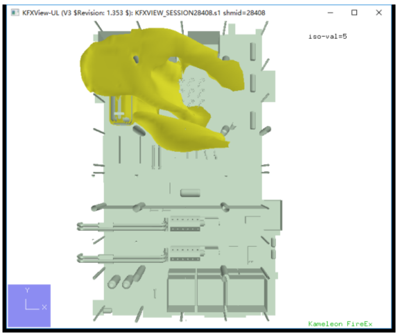
135°



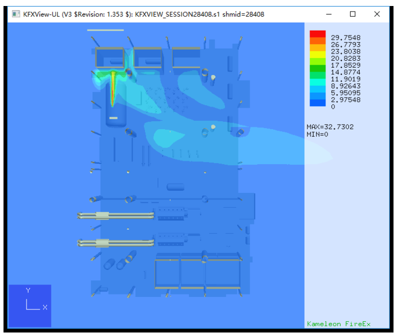
180°



180°



225°



225°

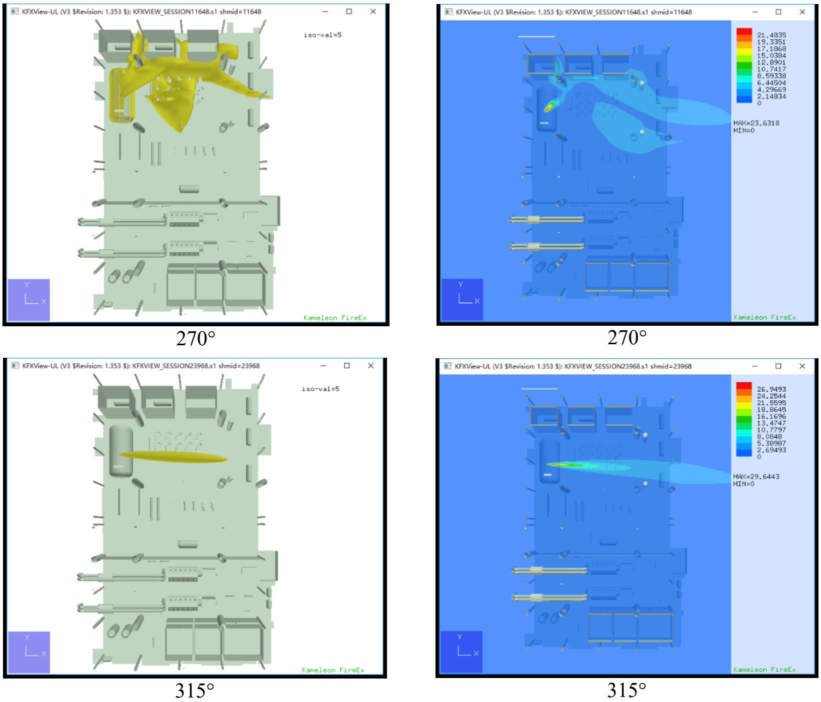


Fig. 7. Distribution of 5% CH_4 cloud under different leakage direction and wind angle

distribution of CH_4 volume on the platform is primarily influenced by the direction of leakage and wind. When the angles are 135° and 315°, the leakage of CH_4 can be approximately seen as a free jet state. The shape of the CH_4 cloud cluster is relatively regular, and only the wind flow has a weak deformation on it. The volume of the 5% CH_4 cloud cluster remains unchanged after reaching a stable value. The influence of the leakage direction on the volume of CH_4 is largely because the equipment and facilities on the axis of the leakage direction change the movement direction and size of the CH_4, thus leading to a change in the shape of the CH_4 cloud cluster. When the angles are 45°, 225° and 270°, the equipment and facilities (such as storage room, control room, explosion-proof wall, etc.) change the direction of movement of CH_4, causing deflection, reflection and other phenomena. At the same time, the motion speed of CH_4 is reduced, and the initial momentum is reduced. In addition, under the action of wind current, the CH_4 cloud is rapidly diluted, further expanding its volume range. By comparing the different angles, it can be seen that when the angles are 0°, 45°, 135°, 180°, 225°, 270°, and 315°, the firewall can effectively prevent the leakage of natural gas from spreading to the non-process area. When the angle is 90°, the natural gas has "bypassed" the explosion-proof wall and diffused to the non-process area, forming a 5% CH_4 area. We can see that in most cases, the methane cloud could be blocked into the process area by the explosion wall, except when the angle is 90°.

3.2. 5% CH_4 cloud volume

3.2.1. Volume-time variation of 5% CH_4 cloud at different leakage mass rates

This paper selects the leakage mass rate of 3 kg/s, 8 kg/s and 20 kg/s respectively. When the wind speed is 7 m/s, and the angle between the wind direction and the leakage direction is 225°, after the leakage, the change of volume of the 5% CH_4 cloud cluster is shown in Fig. 8 below.

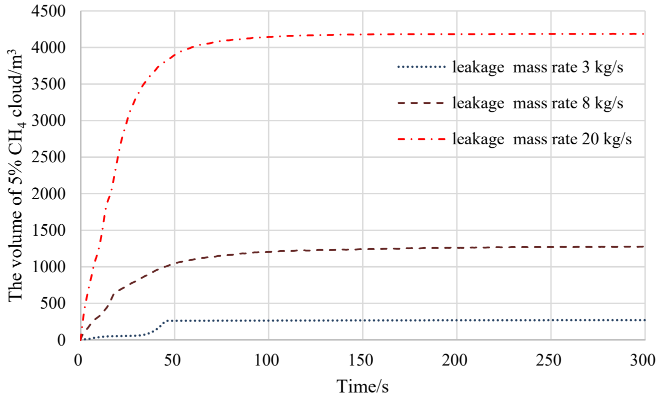


Fig. 8. The variation of 5% CH_4 volume with leakage time at different leakage mass rates

As shown in Fig. 8, for a certain leakage mass rate, the volume of the 5% CH_4 cloud gradually increases with time and then tends to remain unchanged. The change in volume of a 5% CH_4 cloud can be divided into three stages: linear growth, nonlinear growth, and stable stages. The linear growth stage is linearly proportional to the leakage time. In the nonlinear growth stage, the volume of the 5% CH_4 cloud increases, but the growth rate decreases. In the stable stage, the cloud volume of 5% CH_4 remains unchanged. The larger the leakage mass rate is, the larger the slope of the curve is in the linear growth stage, indicating that the volume of the 5% CH_4 cloud increases faster. The higher the mass rate of leakage, the larger the size of the 5% CH_4 cloud in its stable stage. Furthermore, with a higher leakage mass rate, the formation of the CH_4 cloud becomes faster, resulting in a larger cloud volume. Ultimately, this leads to the creation of a larger danger area.

3.2.2. Volume-time variation of 5% CH_4 cloud at different wind speeds

This paper selects the wind speeds of 1 m/s, 7 m/s, and 13 m/s, respectively. When the leakage mass rate is 20 kg/s, and the angle between the wind direction and the leakage direction is 225°, after the leakage, the change of the volume of the 5% CH_4 cloud is shown in Fig. 9.

As shown in Fig. 9, for different wind speeds, the volume of the 5% CH_4 cloud gradually increases with time, and it is divided into the linear growth stage, nonlinear growth stage, and stable stage. The higher the wind speed, the shorter the time for the volume of the 5% CH_4 cloud to reach the stable stage, and the smaller the volume of the 5% CH_4 cloud during the stable stage.

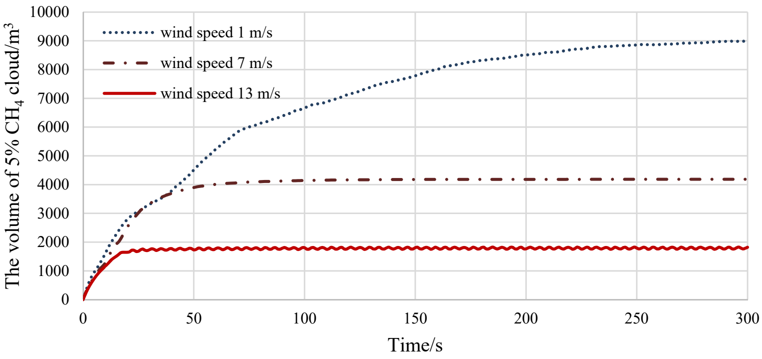


Fig. 9. The variation of 5% CH_4 volume with leakage time at different wind speeds

By comparison, it is found that when the wind speed is 1 m/s and 7 m/s, the volume of the 5% CH_4 cloud curve is very straight and has no fluctuation in the stable stage. When the wind speed is 13 m/s, although the volume of the 5% CH_4 cloud has reached the stable stage, its volume value still fluctuates in a small range. It can be seen that when the wind speed value is high, on the one hand, the dilution of the cloud by the wind current causes the CH_4 concentration to rapidly drop below 5%, and the volume of the 5% CH_4 cloud decreases; on the other hand, the airflow is in the turbulent state, and the CH_4 cloud has the rapid exchange of materials with the surrounding atmosphere, showing stable small-range fluctuations.

3.2.3. Volume-time variation of 5% CH_4 cloud at different angle between wind direction and leakage direction

In this paper, when the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angles between the wind direction and the leakage direction are 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°, the change of the volume of the 5% CH_4 cloud after leakage, as shown in Fig. 10 below.

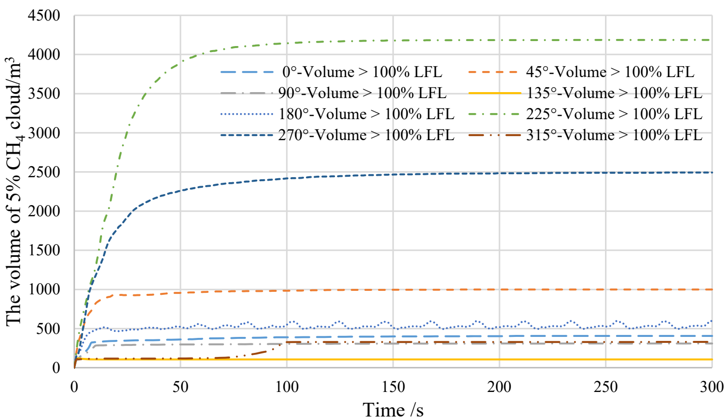


Fig. 10. The variation of 5% CH_4 volume with leakage time at different angles between wind direction and leakage direction

It can be seen from Fig. 10 that for different angles between the wind direction and leakage direction, the volume of the 5% CH_4 cloud in the stable stage is different, and the order of the volume value is: 225°>270°>45°>180°>0 °>315°>90°>135°. The order of the time for the volume of the 5% CH_4 cloud to reach the stable value is: 135°>315°>0°>90°>180°>45°>270°>225°, which is the opposite of the order of the cloud volume value. According to the leakage direction, the location of the leakage point, and the obstacles around the leakage point, for the two situations where the angles are 225° and 227°, on the one hand, the equipment room plays a role in gathering CH_4, on the other hand, the equipment room blocks the wind flow, which significantly weakens its dilution of CH_4 cloud and promotes the increase of the volume of 5% CH_4 cloud. For an angle of 180°, the volume of the 5% CH_4 cloud exhibits a certain fluctuation value after reaching the stable stage. This is mainly due to the fact that the wind flow and the initial movement of the CH_4 cloud "collision" when the wind direction is opposite to the leakage direction. For the angles of 0°, 90°, 135°, 180°, and 315°, the volume value of the CH_4 cloud in the stable stage is relatively small. The main reason is the "impact" effect of the wind current on the CH_4 cloud, which reduces the concentration of CH_4 to 5% or less. We can conclude that when the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angle between the leakage direction and the direction is 225°, the 5% CH_4 volume is the biggest of all.

3.3. Variation law of the stability value of 5% CH_4 volume

3.3.1. Changes of stability value of 5% CH_4 volume at different wind speeds

When the leakage mass rates of natural gas are 3 kg/s, 8 kg/s, 20 kg/s, and wind speeds are 3 m/s, 7 m/s, and 13 m/s, in different leakage angles and wind directions, the changes of the volume stability value of the 5% CH_4 cloud at the angle are shown in (a), (b), (c) of Fig. 11 below.

According to the conclusions in 3.2, we could find that when the angle between the wind direction and leakage is 225°, the 5% CH_4 volume is usually the biggest of all. Besides, we also find from Fig. 10(a), (b) and (c) that the stability value of the 5% CH_4 volume changes with the angle in a wave-like variation. It is at the peak when the angles are 45° and 225°, the biggest located at 225°.

Generally, the more air speed, the methane cloud is more easily to be diluted, and the small size of 5 CH_4 clouds formed. This law is depicted in Fig. (a) and (c). While the "coupling effect" appeals in Fig. 10(b), the biggest volume is the air speed is 7 m/s, reflecting the largest "coupling" effect of air speed, leakage angle and leakage mass rate. The condition of this phenomenon is that the line connecting between the leak point and the geometric centre point of the platform is consistent with the wind direction, and the leak direction is opposite to the wind direction. When CH_4 with a certain initial momentum is injected, it will be blown away under the impact of a certain wind current, and blow toward the platform along the line connecting between the leak point and the geometric centre point of the platform.

3.3.2. Changes of stability value of 5% CH_4 volume at different leakage rates

When the wind speeds are 3 m/s, 7 m/s, and 13 m/s, and the leakage mass rate of natural gas is 3 kg/s, 8 kg/s, and 20 kg/s, the variation of volume stability value of 5% CH_4 cloud at different leakage angle and wind direction is shown in Fig. 12(a), (b), (c).

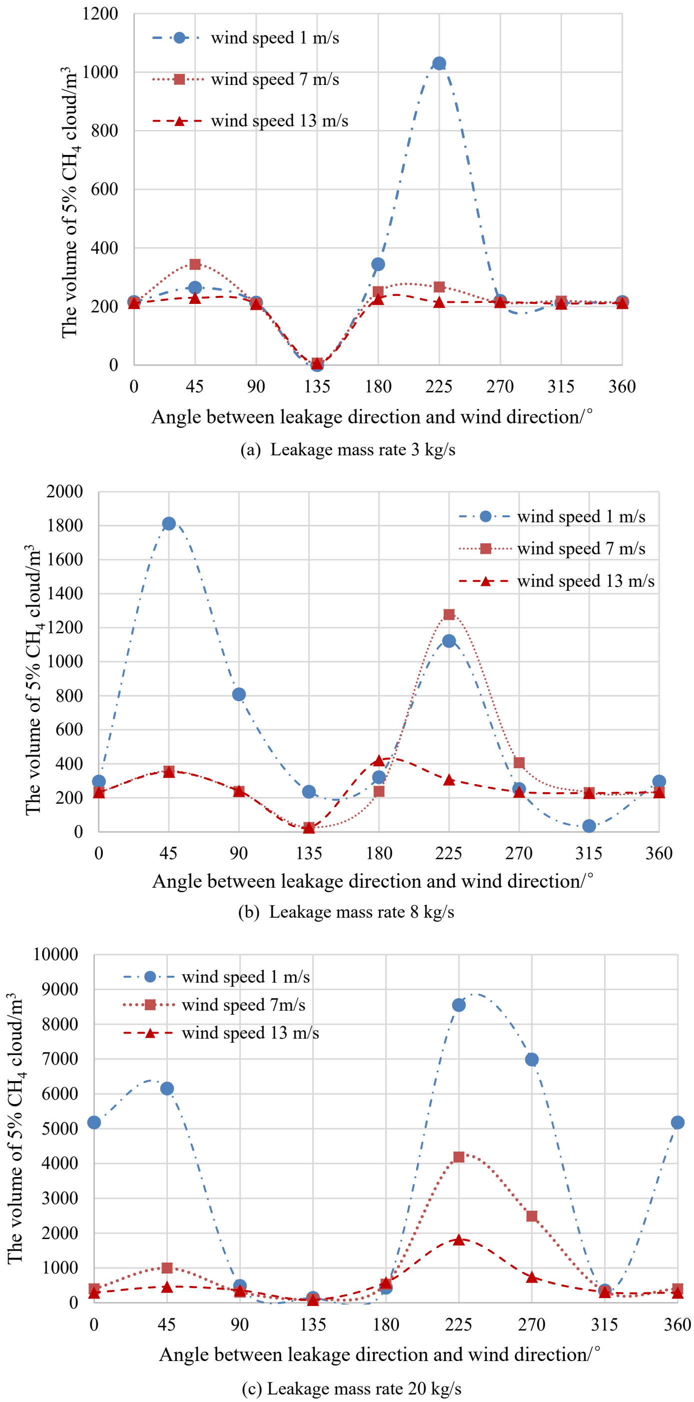


Fig. 11. The variation of stability value of 5% CH_4 volume at different leakage mass rate and wind speed

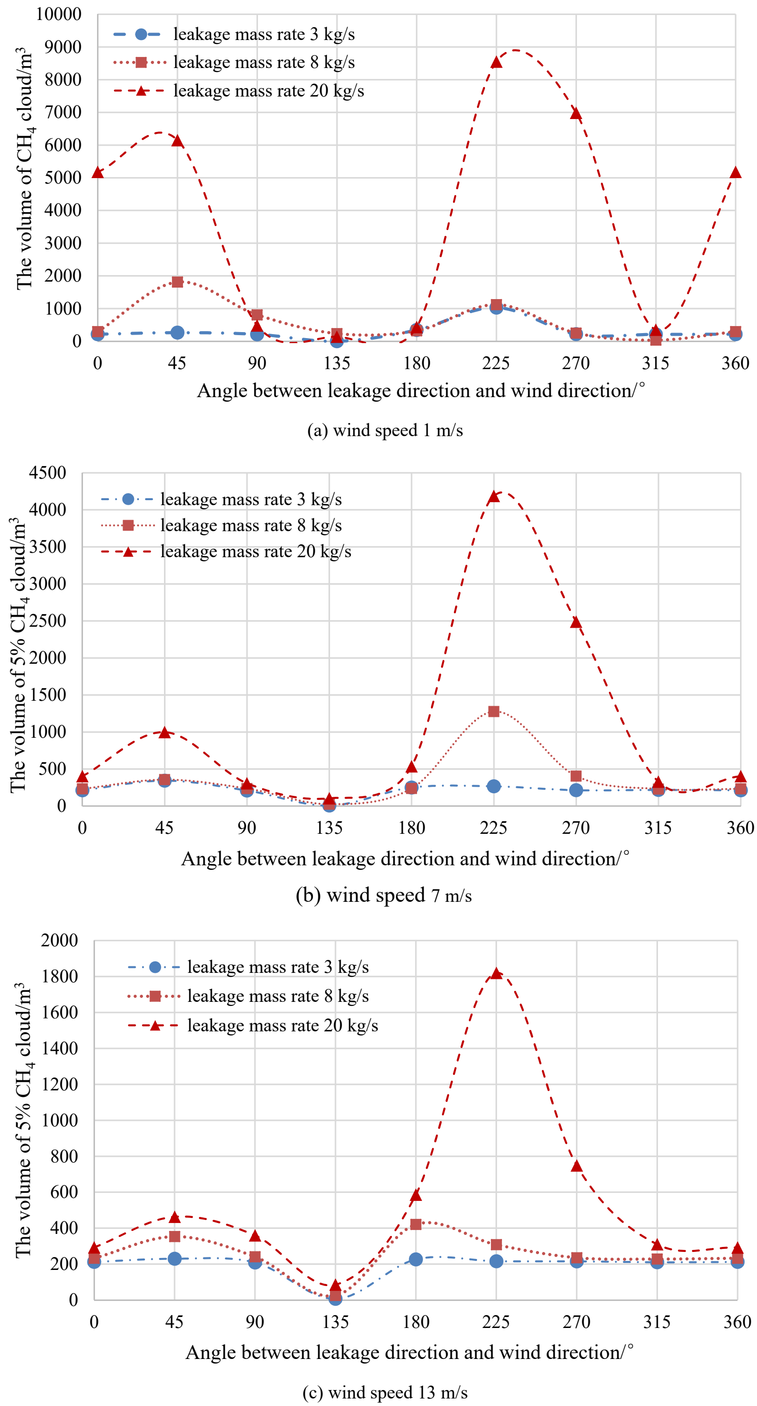


Fig. 12. The variation of stability value of 5% CH_4 volume at different wind speed and leakage mass rate

Generally, the more methane leakage, the bigger the 5% CH_4 volume formed. We can conclude from Fig. 11(a), (b) and (c) that the peak values at 225° are increasing with the leakage rate. While the "coupling effect" appeals in Fig. 11(a), that is the 5% CH_4 volume under leakage rate at 3kg/s and 8 kg/s are almost the same, reflecting the "coupling" effect of air speed and leakage mass rate. Fig. 11(c), demonstrates that the peak volume of 5% CH_4 at 180°, reflects the "coupling" effect between angle and leakage rate. Under certain wind speed conditions, the "coupling" of the leakage mass rate and the angle between the leakage direction and the wind direction affect the volume stability value of the 5% CH_4 cloud.

4. Conclusions

Taking the offshore fixed platform as an example, this paper establishes the geometric model of the platform to simulate the leakage of natural gas dispersion at different leakage mass rates, wind speed, leakage direction and direction angle. This paper studies the spatial and temporal distribution and morphological variation of CH_4 cloud volume in natural gas and draws the following conclusions:

(1) In the early stage of leakage, the concentration distribution of CH_4 is mainly affected by the main wind direction and migrates along the wind direction. With the increase in leakage time, the concentration distribution of CH_4 is mainly affected by the wind flow and the barrier of the explosion wall. The explosion-proof wall on the platform can effectively prevent the diffusion of leaking natural gas, reduce its diffusion area, and reduce the consequence of explosion after leakage.

(2) We can conclude that when the leakage mass rate is 20 kg/s, the wind speed is 7 m/s, and the angle between the leakage direction and the direction is 225°, the 5% CH_4 volume is the biggest of all.

(3) The volume stability value of the 5% CH_4 cloud shows a wave-like variation with the angle. There is a "coupling" effect between wind speed, leakage angle and leakage mass rate. When the leakage rate is 8 kg/s, the airspeed is 7 m/s (angle is fixed), and the 5% CH_4 volume is the biggest of all, reflecting the largest "coupling" effect of air speed, leakage angle and leakage mass rate.

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