ISSN: 2688-8645

Leakage Hazard Analysis of Hydrogen Blended Natural Gas Station Field Based on PHAST

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Abstract

To investigate study the leakage and diffusion characteristics of hydrogen-blended natural gas in station fields, simulation calculations and safety analyses of combustible gas diffusion, fire, and explosion for different leakage scenarios were conducted using PHAST software by DNV., A risk map for personnel in the station field was then generated. The results indicate that large-hole leaks primarily spread near the surface, while small-hole leaks rapidly disperse to higher altitudes due to factors such as flow rate, wind speed, and gravity. In the event of a jet fire, the thermal radiation at the fire's center quickly rises to its maximum value, stabilizes, and then gradually decreases to its minimum. When an explosion occurs, the affected area expands significantly with an increase in hole diameter. These findings provide guidance for equipment and pipeline placement, hazardous area zoning, and emergency response procedures following station reconstruction.

Keywords

Hydrogen Blended Natural Gas; PHAST; Leakage Explosion; Simulation Analysis.

1. Introduction

The 'dual-carbon target' should be comprehensively integrated into the medium- and long-term planning for economic and social development. This includes promoting energy conservation, emission reduction, and cleaner production, accelerating the development of a circular economy, strengthening resource utilization, and continuously advancing green and low-carbon development [1]. The role of renewable energy as a clean energy alternative is becoming increasingly prominent. However, due to regional economic disparities in China, the central and western regions face challenges in locally utilizing electricity generated by wind and other renewable sources, leading to significant resource waste in some areas. Currently, Hydrogen-Doped Natural Gas (HDNG) technology is widely recognized as an effective solution to the issue of 'wind and light abandonment.' This technology converts part of the wind and solar energy into electricity for water electrolysis to produce hydrogen, which is then blended with natural gas at a specific ratio. The mixture is delivered to user terminals, gas filling stations, and storage reservoirs via the existing or newly built natural gas pipeline network[2-5]. thereby avoiding the high costs of constructing new hydrogen pipelines and providing valuable insights for the industrialization of hydrogen energy.

ISSN: 2688-8645

Hydrogen and natural gas are both flammable and explosive substances. When their concentration in the air reaches the lower explosion limit, they can ignite and explode upon contact with an open flame. Conversely, if the concentration is below the lower explosion limit, ignition by an open flame can result in intense combustion. Therefore, analyzing the leakage and diffusion of hydrogen-doped natural gas, and understanding its movement patterns, is essential for informing the current arrangement of natural gas gate stations, determining emergency response measures, and delineating alarm zones in the event of a hydrogen-doped natural gas leak. The leakage and diffusion process of hydrogen-doped natural gas is complex, involving dynamic phenomena such as multi-component transport, turbulent flow, and heat transfer.

Peng et al. [6]analyzed the effects of hydrogen doping ratio, leakage aperture, wind speed, and atmospheric temperature on the diffusion of hydrogen-doped natural gas leaks in long-distance pipelines using both single-factor and multifactor coupling approaches. Zhang et al. [7] employed numerical simulations to establish a mathematical model for leakage diffusion in direct-buried, high-pressure hydrogen-doped natural gas pipelines, analyzing the impact of different hydrogen doping ratios on leakage conditions, the distribution of volume fractions, ground pressure around the pipeline, and gas leakage velocity. Chen et al. [8] used FLACS to simulate the evolution of hydrogen-doped natural gas leakage under various scenarios, analyzing the effects of factors such as hydrogen doping ratio, leakage aperture, leakage pressure, and leakage temperature. Song et al. [9] employed FLACS software to study the impact of wind speed on the consequences of hydrogen-doped natural gas station accidents under different wind conditions.

The PHAST software package, developed by DNV, the Norwegian classification society, integrates accident frequency with process data to calculate the range of fire heat radiation and explosion shock waves from simulated accidents [10]. This paper uses PHAST software to model a hydrogen-doped natural gas station site, focusing on various leakage apertures and devices for leakage analysis. thereby providing valuable guidance for equipment arrangement at the station site.

2. Modelling of Hydrogen Doped Natural Gas Leaks

The hazardous consequences of a hydrogen-doped natural gas leak include jet fires, flash fires, and explosions. Table 1 outlines the key factors and risk implications associated with these different leakage hazards [11]. The PHAST software employs the Unified Dispersion Model (UDM) to simulate the dispersion concentration of hydrogen-doped natural gas leaks over time and delineates the safety zone by illustrating the cloud extent and downwind distance using isoconcentration lines as range indicators[12, 13]. Figure 1 shows a schematic of the leakage propagation of hydrogen-doped natural gas.

Table 1. Consequence scenarios for leakage of hydrogen-doped natural gas

Result	Key Factors	Combustion Description	Risk
Jet fire	Continuous leak spread, immediate ignition	Momentum-driven non-premixed turbulent flame. Burning speed roughly equal to leakage speed	Thermal effect
Flash fire	Accumulated gas deflagration, delayed ignition	Equivalent to pre-mixed flame combustion, which is faster than the leakage of hydrogen-doped gas into the air	Thermal effect
Explosion	Accumulated gas deflagration or detonation, delayed ignition	Rapid flame propagation in confined spaces, with shock waves from either deflagration or detonation	Overpressure effects

ISSN: 2688-8645

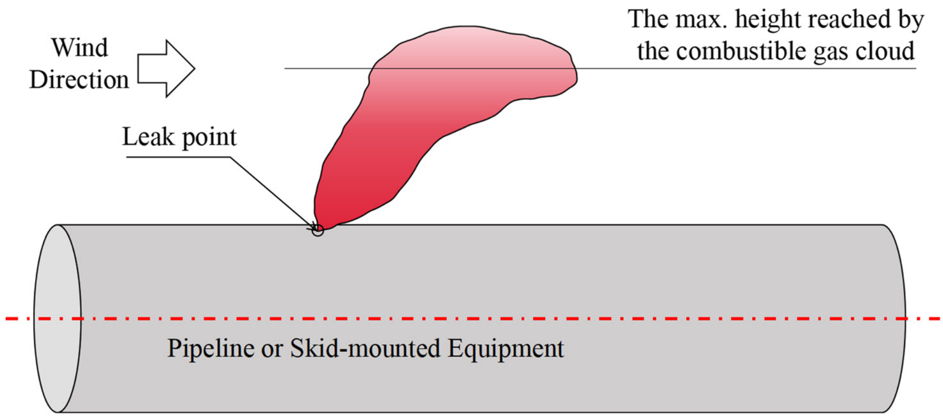

Figure 1. Leak diffusion model for hydrated natural gas

2.1. Diffusion Model for Leakage

2.1.1. Transient Leakage Diffusion Model

Equation (1) gives the mass concentration of hydrogen-doped natural gas diffused into the air by leakage through the vent [14].

$$C(x,y,z)=C_0(x)\exp\left\{-\left|\frac{z}{\sqrt{2}\sigma_z}\right|^{n(x)}\right\}\exp\left\{-\left|\frac{y}{\sqrt{2}\sigma_y}\right|^{m(x)}\right\} \tag{1}$$

Where: C_0 is the centreline mass concentration, kg/m3; x is distance in downwind direction, m; y is distance in the side wind direction, m; z is distance in the side wind direction, m; σ_z is vertical diffusion parameter of standard deviation of mass concentration, m; σ_z is horizontal diffusion parameter of standard deviation of mass concentration, m; *n(x)* is exponential of the vertical wind direction distribution function of mass concentration, no dependent term; *m(x)* is exponential of the horizontal wind direction distribution function of the mass concentration, no dependent term.

2.1.2. Continuous Leakage Dispersion Model

$$C(x,y,\zeta,t)=C_0(t)\exp\left\{-\left|\frac{\zeta}{\sqrt{2}\sigma z}\right|^{n(x)}\right\}\exp\left\{\left[\left(\frac{x-x_{cld}(t)}{Rx(t)}\right)^2+\left(\frac{y}{Ry(t)}\right)^2\right]^{\frac{m}{2}}\right\} \tag{2}$$

Where: ζ is the distance from the centreline of the plume, *m*; $x_{cld}(t)$ is distance downwind from the centre spread of the air cloud at the moment *t*, *m*; *Rx(t)* is the downwind and side wind direction diffusion coefficients at the moment *t*. *Ry(t)* is the diffusion coefficient in the downwind and side wind direction at the moment of *t*.

2.2. Thermal Radiation Modelling

Hydrogen-doped natural gas forms a high-pressure jet stream at the leak opening, which, under the ignition conditions of an ignition source, can lead to the formation of a jet fire. The amount of heat radiation from the jet fire is calculated using the Thornton model [15], as follows:

$$I=\frac{\eta jQH_c T_{jet}}{4\pi r^2} \tag{3}$$

Where: I is the incident radiation, kW/m2; Q is the mass release flux, kg/s; r is the radius of injury, m; η is the efficiency factor, for methane, take 0.2; H_c is the heat of combustion of hydrogen-doped natural gas, J/kg; T_{jet} is the radiance factor, taken as 1.

The intensity of thermal radiation can cause varying degrees of damage to people, equipment, and buildings near the combustion and explosion site. If the amount of thermal radiation to

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which a target is exposed equals or exceeds the critical threshold required to cause damage, the target will be harmed [16] [17]. Guidelines for determining the risk of exposure to thermal radiation are given in Table 2 [18]

Table 2. Criteria for determining thermal radiation quantity

Thermal radiation /(KW/m2)	Equipment risks	Risks to the human body
4~5	No apparent harm	Painful at 20 seconds exposure; first degree burns at >30 seconds exposure
12.5~15	Minimum energy for wood to burn and plastic to melt when a flame is present	First degree burns after 10 seconds of exposure, 1% lethality within 1 minute
25	Minimum energy for wood to burn and plastic to melt in the absence of flame	Severe burns within 10 seconds of exposure, 100 per cent lethality within 1 minute
35~37.5	Damage to operational equipment	1% lethality in 1 second

2.3. Vapour Cloud Explosion Model

When hydrogen-doped natural gas leaks and diffuses into the air, it forms vapor clouds that can explode if the concentration reaches the explosive limit and comes into contact with an ignition source. Currently, the main methods for calculating overpressure from hydrogen and natural gas explosions include the equivalent TNT method, the TNO method, and the Baker-Strehlow method [19]. TNT-equivalent models are commonly used for vapor cloud explosions to calculate the overpressure of the blast wave.

$$W_{\mathrm{TNT}} = \frac{1.8\alpha W_{\mathrm{f}} H_{\mathrm{c}}}{H_{\mathrm{TNT}}} \tag{4}$$

Where: α is the TNT equivalence factor, taken as 4 per cent; W_f is the mass of fuel in the vapour cloud, kg; H_c is the heat of combustion of hydrogen-doped natural gas, MJ/kg; H_{TNT} is the heat of explosion of TNT, taken as 4.52 MJ/kg.

When an explosion occurs at the surface with a scalar quantity of W_{TNT}, the explosion overpressure ΔP and explosion radius R are calculated using Eq. (5) and (6).

$$\Delta P = 12.6 \times \left| \frac{\sqrt[3]{W_{\mathrm{TNT}}}}{R} \right|^{3} + 3.99 \times \left| \frac{\sqrt[3]{W_{\mathrm{TNT}}}}{R} \right|^{2} + 1.02 \times \left| \frac{\sqrt[3]{W_{\mathrm{TNT}}}}{R} \right| \tag{5}$$

$$R = 13.6 \times \left(\frac{W_{\mathrm{TNT}}}{1000} \right)^{0.37} \tag{6}$$

The shock wave generated by explosion overpressure can cause varying degrees of damage to people and buildings. Guidelines for the damage to buildings and personnel caused by blast overpressure are provided in Tables 3 and 4 [11].

3. Environmental Condition

This paper presents a simulation analysis based on the fundamental data of a station, examining the consequences of leakage accidents involving hydrogen doping skids, separation skids, and buried hydrogen doping pipelines to be installed and used at the station. The simulation primarily focuses on leakage explosions resulting from corrosion perforations (5 mm) and accidental ruptures (50 mm) of the three devices, assuming a hydrogen doping ratio of 30%.

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Table 3. Criteria for determining damage to buildings from blast overpressure shock waves

Blast overpressure	Risks to buildings
0.5~2 kpa	Glass partially broken
2~12 kpa	Glass completely broken
12~30 kpa	Doors and windows damaged, small cracks on brick wall
30~50 kpa	Brick wall cracks 0.5~5mm, steel roof cracking
50~76 kpa	50mm cracks on wall, severe cracks on steel roofing
76~100 kpa	Brick wall collapsed, steel roof caved in

Table 4. Criteria for determining injury to personnel from blast overpressure shock waves

Blast overpressure	Level	Degree of damage
20~30 kpa	Light	Middle ear, lung damage
30~50 kpa	Medium	All the glass is broken.
50~100 kpa	Severity	Damaged windows and doors, small cracks in brickwork
>100 kpa	Deaths	Cracks in brick walls 0.5~5mm, cracks in steel-concrete roofs

3.1. Weather Basis Conditions

The Station is located in a northern subtropical monsoon climate zone, characterized by abundant sunshine with an average of approximately 2,000 hours of sunshine annually. Rainfall is also sufficient, with an average annual precipitation of about 1,170 mm. The temperature variation between cold and warm periods is relatively small, and the hot and cold seasons are brief, with an average annual temperature of around 16°C. The region experiences an average of 135 rainy days per year, and the prevailing wind direction is from the southeast, with an average annual wind speed of 3.4 m/s.

3.2. Equipment Base Data

The gas components at the station site after hydrogen doping include methane, hydrogen, ethane, propane, and nitrogen. Of these, natural gas constitutes 68.52%, hydrogen accounts for 30%, nitrogen makes up 0.60%, ethane represents 0.20%, and propane comprises 0.01%. The design parameters of each unit are shown in Table 5.

Table 5. Design parameters for station units

Units	Pressure	Temperature	Mass flow	Diameter of pipeline
Hydrogen blending skid	0.4 Mpa	30℃	270.5kg/h	200mm
Separation skid	4 Mpa	30℃	18.93kg/h	200mm
Pipeline	4 Mpa	30℃	270.5kg/h	200mm

4. Results and Discussion

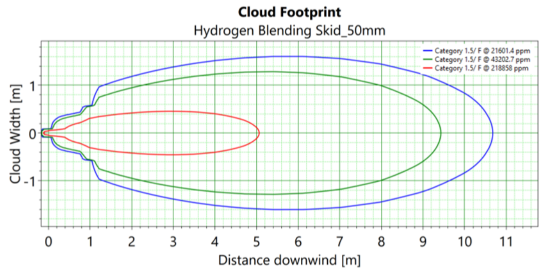
4.1. Vapour Cloud Dispersal Area of Influence

When the vapor cloud produced by hydrogen-doped natural gas leakage spreads in the air, varying gas cloud concentrations can lead to different accident outcomes. The relationship between vapor cloud concentration and the resulting accident consequences in the region is shown in Table 6 [20].

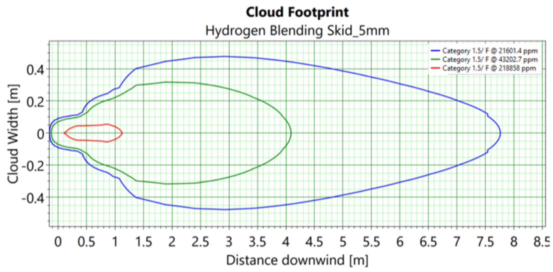
Table 6. Relationship between vapour cloud concentration and accident consequences

Sphere of influence	Gas cloud concentration	Consequences of accidents in the region
≤50%LEL	21601.4 PPM	Safety area
LEL~UEL	43202.7 PPM	Flammable and explosive area
≥UEL	218858 PPM	High risk area

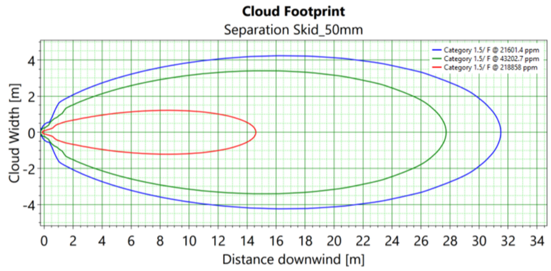
As the vapor cloud disperses outward from the leak point, the extent of the hazardous area increases due to its own gravity and the influence of external wind. The footprint view of the vapor cloud after leakage, under different leakage conditions, is shown in Figure 2.



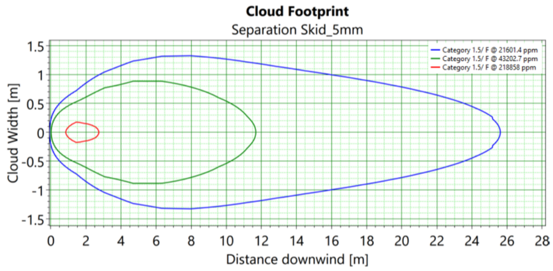
(a) Hydrogen blending skid_50mm



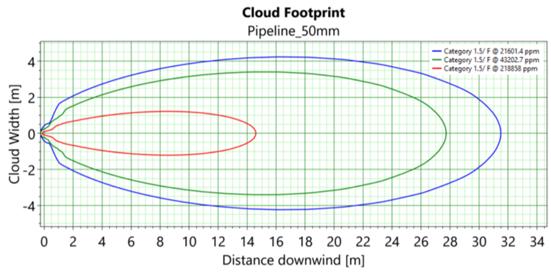
(b) Hydrogen blending skid_5mm



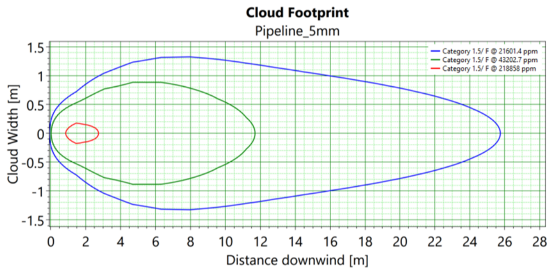
(c) Separation skid_50mm



(d) Separation skid_5mm



(e) Pipeline_50mm



(f) Pipeline_5mm

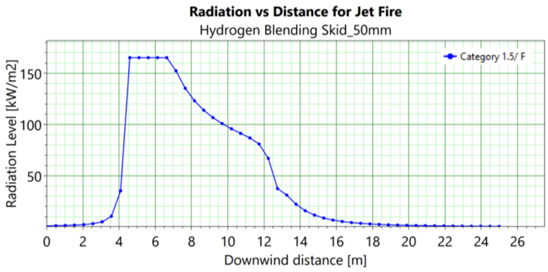
Figure 2. Footprint of vapour cloud under different operating conditions

As shown in Figure 2, under the 50 mm large hole leakage conditions, the concentration of the combustible vapor cloud is less than 50% of the lower explosive limit, and the extent of the vapor cloud is larger than that of the vapor cloud from a 5 mm leakage hole. In the case of large-hole leakage from the separation skid, the vapor cloud, with a concentration below 50% of the lower explosive limit, can reach a maximum downwind diffusion distance of 14.6 m. This indicates that large-hole leakage tends to cause more surface-level dispersion, while small-hole leakage, due to factors such as flow rate, wind speed, and gravity, spreads quickly to higher altitudes. Therefore, when setting up outdoor gas leak detectors, emphasis should be placed on monitoring the concentration of flammable gases near the ground surface to prevent the risk of combustion and explosion. A warning line should also be established around high-risk areas to prevent unauthorized personnel from entering.

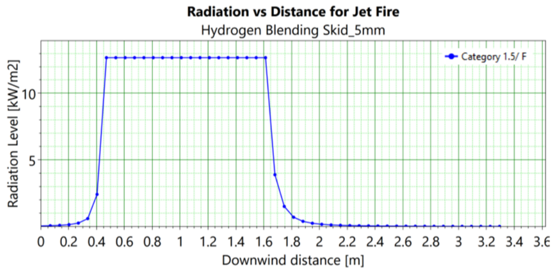
4.2. Area of Influence of Jet Fires

Hydrogen and natural gas are both flammable and explosive substances. When a leak occurs, hydrogen-doped natural gas forms a high-pressure jet at the leak site, which can ignite and result in a jet fire. When the heat radiation intensity exceeds a certain threshold, it can cause varying degrees of damage to the human body. Figure 3 shows the intensity of heat radiation and the horizontal distance of the jet fire caused by the leakage of hydrogen-doped natural gas under different operating conditions.

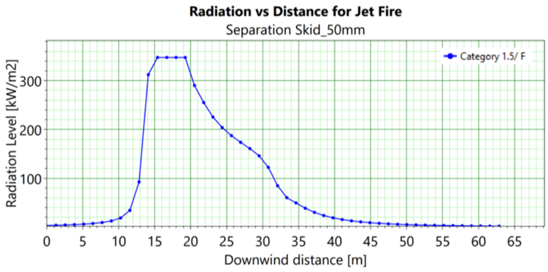
ISSN: 2688-8645



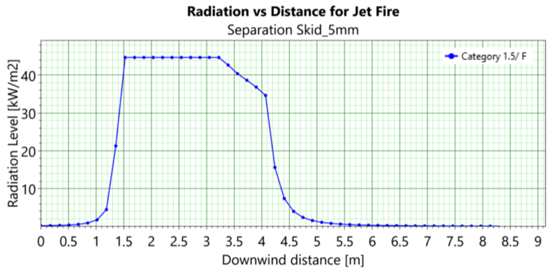
(a) Hydrogen blending skid_50mm



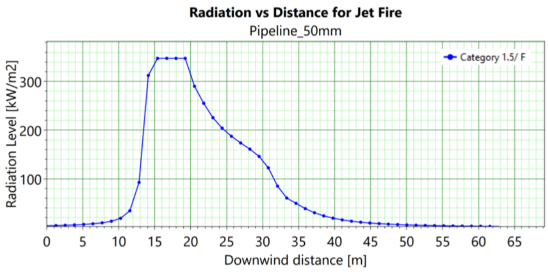
(b) Hydrogen blending skid_5mm



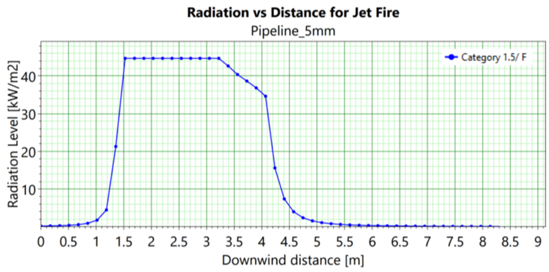
(c) Separation skid_50mm



(d) Separation skid_5mm



(e) Pipeline_50mm



(f) Pipeline_5mm

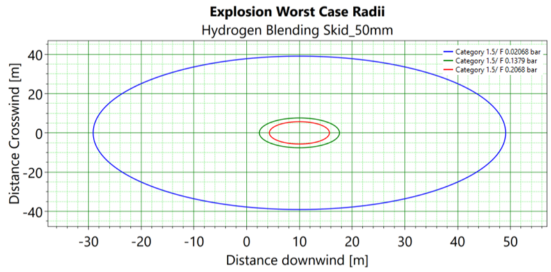
Figure 3. Thermal radiation intensity of jet fire under different working conditions

The analysis results show that, after a jet fire accident occurs, the hazard level from small-hole leakage in the hydrogen doping skid is lower, but still exceeds 12.5 kW/m^2. In contrast, for other operating conditions, the radiation intensity exceeds 37.5 kW/m^2, with 1% lethality occurring within 1 second. The furthest downwind distance within the 12.5 kW/m^2 radiation range is 42.4 meters, while in the 37.5 kW/m^2 radiation range, the furthest downwind distance is 36.1 meters. These findings suggest that controlling fire sources in this operational environment is crucial to prevent major casualties caused by the thermal radiation from jet fires.

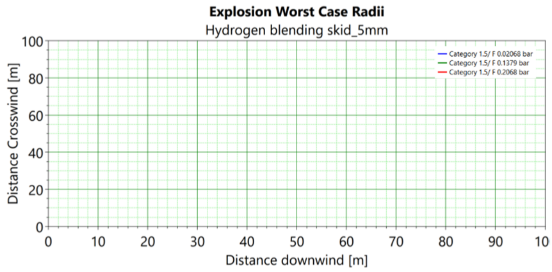
4.3. Explosive Overpressure Shock Wave Impact Area

When hydrogen-doped natural gas leaks, it forms vapor clouds in the air. If the concentration reaches the explosive limit, an explosion can occur upon contact with an ignition source. Figure 4 shows the overpressure radius resulting from hydrogen-doped natural gas leakage under various operating conditions after an explosion.

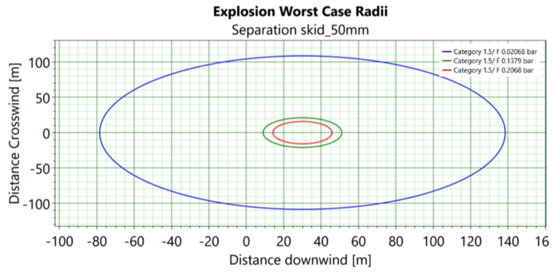
The analysis indicates that, in the event of a leakage explosion, the explosion impact area increases significantly as the hole diameter increases, affecting a larger portion of the entire station. However, in the case of small-hole leakage from the hydrogen-doped skid, the low pressure and small hole diameter prevent an explosion. To ensure the stable operation of the station and the safety of surrounding facilities, hazardous areas should be properly delineated, and critical equipment should be placed outside these zones.



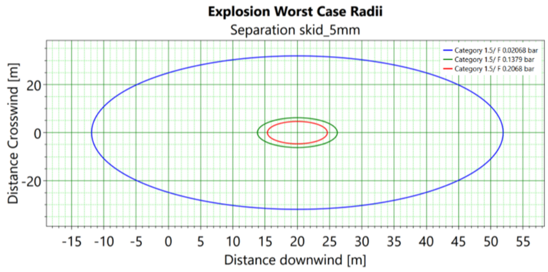
(a) Hydrogen blending skid_50mm



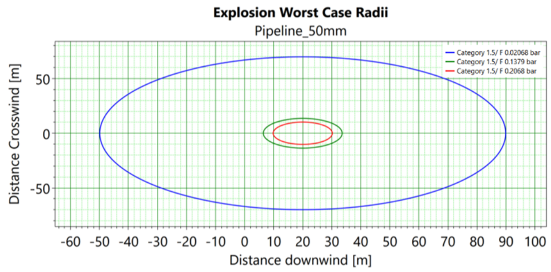
(b) Hydrogen blending skid_5mm



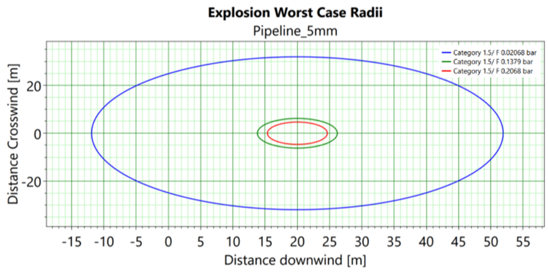
(c) Separation skid_50mm



(d) Separation skid_5mm



(e) Pipeline_50mm



(f) Pipeline_5mm

Figure 4. Explosion overpressure radius curve under different working conditions

4.4. Risk Evaluation

To ensure the effective follow-up of the station reconstruction, risk simulations were conducted based on established models of hydrogen-doped natural gas leakage under various operating conditions. The simulations were performed using the DNV_SAFETI software, resulting in contour plots of individual risks, as shown in Figure 5.

(a) Hydrogen blending skid

(b) Separation skid

(c) Pipeline

Figure 5. Individual risk contour

Based on the distribution of personnel at the station and the analysis in Figure 5, it can be observed that after a leakage and explosion accident, the affected area is far from where people are gathered, and therefore, it does not result in casualties. However, given the complexity of internal personnel movement within the station, attention should be given to the planning of area distribution to minimize the risk of injury.

5. Conclusion

The simulation and analysis of hydrogen-doped natural gas leakage incidents at the station site, conducted using the PHAST software, led to the following conclusions:

(1) Large-hole leaks tend to spread near the ground surface, while small-hole leaks rapidly rise to higher altitudes due to factors such as flow velocity, wind speed, and gravity. When installing outdoor gas leak detectors, attention should be focused on the concentration of flammable gases near the surface to mitigate the risk of ignition and explosion.

(2) In the event of a jet fire, the thermal radiation value at the combustion center quickly increases to its maximum, stabilizes, and then gradually decreases to its minimum.

(3) During leakage and explosion incidents, the explosion impact area significantly increases with the hole diameter, affecting the entire station. However, hydrogen-doped skid small-hole leaks, due to their low pressure and small hole diameter, do not result in explosions.

(4) Based on the station's personnel distribution map, leakage and explosion accidents do not impact casualties. However, due to the complexity of personnel movement within the station, preventive and control measures should be implemented in these areas to minimize the risk of injury to personnel.

Acknowledgments

This research was supported by the National Natural Science Foundation of China for Young Scholars (Grant Nos. 51904259), the National Natural Science Foundation of China joint fund for enterprise innovation and development (Grant Nos.U19B2012).

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