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Research Article

Numerical Simulation and Analysis of Diffusion Process for the Leakages of a Tunnel LNG Pipeline

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Taking a practical project as an example, based on the computational fluid dynamics (CFD), standard k-ε model and finite element method, a mathematical model for the diffusion due to liquefied natural gas (LNG) pipeline leakage in a tunnel was established, and the diffusion process was numerically simulated for three LNG leakage cases. From the simulation results, the variation of CH_4 concentration field and explosive gas cloud with time within the tunnel, and the influence of leakage location on the diffusion was analyzed for the three cases. It was shown that the variation of CH_4 concentration field had a similar trend for the three cases, but the CH_4 explosive gas cloud length increased rapidly with the LNG leakage intensity so that dangerous situations would occur for the medium and large leakages, and a leak location closer to air inlet would lead to a more dangerous situation. When the amount of LNG leakage in the tunnel is large, the effect of mechanical ventilation is obviously weakened. Furthermore, a nitrogen seal precaution was proposed for the situations.

1. Introduction

Liquefied natural gas (LNG) is an efficient, clean, and relatively inexpensive energy source and widely used in every daily life, industrial production, and other fields. It has become one of the three pillars of the world's energy with the volatile international oil price and the rapid growth of the demand for clean energy [1]. In recent years, LNG pipeline leakage within the tunnel has attracted more and more concerns. The CH_4 gas clouds will not only infect human health but also cause an explosion accident when it encounters heat or open flame as well [2]. The range of explosion limit for natural gas in the air is 5.3%~15.1% [3], and the area between the explosion limits is called the explosive gas cloud area. Ensuring people's safety is a paramount concern due to the flammable and explosive nature of LNG, with leakage causing many serious accidents and enormous loss. For example, in 1944, an LNG leakage explosion occurred at an LNG station in Cleveland, USA. The explosion spread over 14 blocks, killed 136 people, and injured 225. The damage extended to 0.75 square miles [4]. In 2004, an LNG receiving terminal in Algeria leaked and caused a fire, resulting in 27 deaths, 74 injuries, and over 1 billion U.S. dollars in damages [5].

The diffusion and explosion models and the combustion fireball from LNG leakage are studied by many researchers. Yue et al. [1] simulated and analyzed the multiple conceivable disasters due to the leakage of LNG storage tanks by using the computational fluid dynamics software FLACS. Lv et al. [6] established a reduced model of 160,000 m^3 LNG storage tank according to the ratio of 1: 100, carried out LNG explosion tests, and simulated the explosion process with FLACS. They established the correlation between the test model and the full-size model explosion overpressure to evaluate the maximum explosion overpressure of large LNG storage tanks. Hu et al. [7] proposed a topological network model and inversion method for LNG tank fire accidents. They established a topological model for LNG tank fire inversion and found the shortest path, according to the weighted edge topological network structure, and to determine the fire location. Ren [8] studied the changing law of temperature in the process of large-area LNG leakage and explosion using numerical methods. Moreover, the numerical model considered the influence of wind speed on the temperature of the escaped liquefied natural gas. Baalisampang et al. [9] developed an evaluation method for cascade accidents caused by LNG leakage. This method uses computational fluid dynamics (CFD) software FLACS simulation of LNG leakage on a series of disasters and considers the evolving scenario, namely, from a liquid pool after LNG evaporation followed by combustion, explosion, and yielding combustion products. Li et al. [10] used FLACS to simulate the development of a flame, overpressure after leakage, and an explosion of a natural gas pipeline. It was found that the length of natural gas chambers and different ignition positions had little influence on overpressure.

The technical tunnel with LNG pipelines (Figure 1) always proposes high requirements for fire safety and structural safety levels. Presently, there are only 2 LNG technical tunnels in the world available for learning. One is the Cove Point LNG Technical Tunnel in Chesapeake Bay, Maryland, USA, with a total length of 1,947 m, parted in the seafloor and the land, of which 1,607 m on the seafloor and 340 m on the land. The former is constructed by the immersed pipe method in the form of a single slope, with joints of pipe sections sealed and waterproof by welding steel plates and filling with concrete. The latter adopts a form of reinforced concrete box culvert section, surrounded by a waterproof layer, constructed by a cofferdam, foundation treatment, and open excavation to dock with the submarine part of the immersed tube tunnel. The other one is the Ohgishima LNG Technical Tunnel in Yokohama Bay, Japan (Figure 1), with a total length of 2,000 m, constructed with the shield method. The world's third LNG technical tunnel is being constructed in Shenzhen, China (Figure 2). In this paper, the LNG leakage and diffusion process in this tunnel is numerically simulated. The diffusion law of LNG in the tunnel under different leakage amounts, the distribution of CH_4 explosion gas cloud, and the influence of location of leakage point to CH_4 diffusion are studied. Then, a protective measure of nitrogen-filling sealing is hereby proposed, which is of great significance to the safety of LNG pipeline leakage within the tunnel.

2. Fundamental Equation of LNG Leakage and Diffusion

The fundamental equations of LNG leakage and diffusion are established with the standard k-ε model [11, 12], with its general form as follows:

$$\frac{\partial}{\partial t}(\bar{\rho}\bar{\varphi}) + \operatorname{div}\left(\bar{\rho}\bar{u}\bar{\varphi} - \Gamma_{\varphi j}\ \operatorname{grad}\bar{\varphi}\right) = \bar{S}_{\varphi}, \quad (1)$$

wherein $\bar{\rho}$ is the time average of smoke density, kg/m^3; $\bar{\varphi}$ is the time average of each variable; $\bar{u}$ is the time-average of velocity vector, m/s; $\Gamma_{\varphi j}$ is the turbulent transport coefficient of φ; S_{φ} is source terms for different φ terms, see Table 1.

Figure 1: Tunnel for LNG pipelines in Ohgishima.

Figure 2: LNG technical tunnel under construction in Shenzhen.

3. Geometric Model

The object in this paper is the world's third LNG technical tunnel being constructed in Shenzhen, China (Figure 3). It is a mountain tunnel, with its entrance at the seaside of Dapeng Bay and its exit about 100 m away from the tank farm. The entrance is 1.75 m higher than the exit. This tunnel has a U-shaped cross-section (Figure 4), with a clearance size of 11.0 × 8.3 m, a length of 594 m, and a slope section length of 60 m. The pipeline design pressure is 688 kPa. There are mechanical vents of 1 m × 1 m arranged at the upper parts of both entrance and exit with a ventilation rate of 1.2×10^5 m^3/h. The LNG pipeline with a diameter of 1.2 m is laid 2 m away from the centerline of the tunnel (Figure 5).

It is assumed that the leakage point of the LNG pipeline is located at the air inlet end of the tunnel (the other end of the tunnel is the exhaust outlet); the fractures in the LNG pipeline are considered as three different diameters of 100 mm, 50 mm, and 10 mm (recorded as Case 3, Case 2, and Case 1) [15, 16]. The tunnel space is meshed with unstructured grids (Figure 5), and numerical simulation is performed with the k-ε turbulence model and SIMPLE algorithm [17].

Assuming that the measuring points in the numerical simulation of LNG diffusion are distributed horizontally (Z

Table 1: Source term in control equation [13, 14].

Equation	φ	Γ	S_φ
Continuity equation	1	0	0
x-momentum equation	u	μ	$(\partial/\partial x)(\mu(\partial u/\partial x)) + (\partial/\partial y)(\mu(\partial v/\partial x)) + (\partial/\partial z)(\mu(\partial w/\partial x)) - \partial p/\partial x$
y-momentum equation	v	μ	$(\partial/\partial x)(\mu(\partial u/\partial x)) + (\partial/\partial y)(\mu(\partial v/\partial x)) + (\partial/\partial z)(\mu(\partial w/\partial x)) - \partial p/\partial y$
z-momentum equation	w	μ	$(\partial/\partial x)(\mu(\partial u/\partial x)) + (\partial/\partial y)(\mu(\partial v/\partial x)) + (\partial/\partial z)(\mu(\partial w/\partial x)) - \partial p/\partial z$
Turbulent momentum equation	k	μ/σ_k	$G - \rho\varepsilon$
Turbulent diffusivity equation	ε	μ/σ_ε	$(\varepsilon/k)(C_1 G - C_2\rho\varepsilon)$
$\mu = \mu_1 + \mu_T$	$\mu_T = C_\mu \rho k^2/\varepsilon$		$G = \mu_T\left(\left(\partial\mu_i/\partial x_j\right) + \left(\partial\mu_j/\partial x_i\right)\right)\left(\partial\mu_j/\partial x_i\right) - \mu_1(g_i\partial\rho/\rho\partial x_i)$
	$C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$		

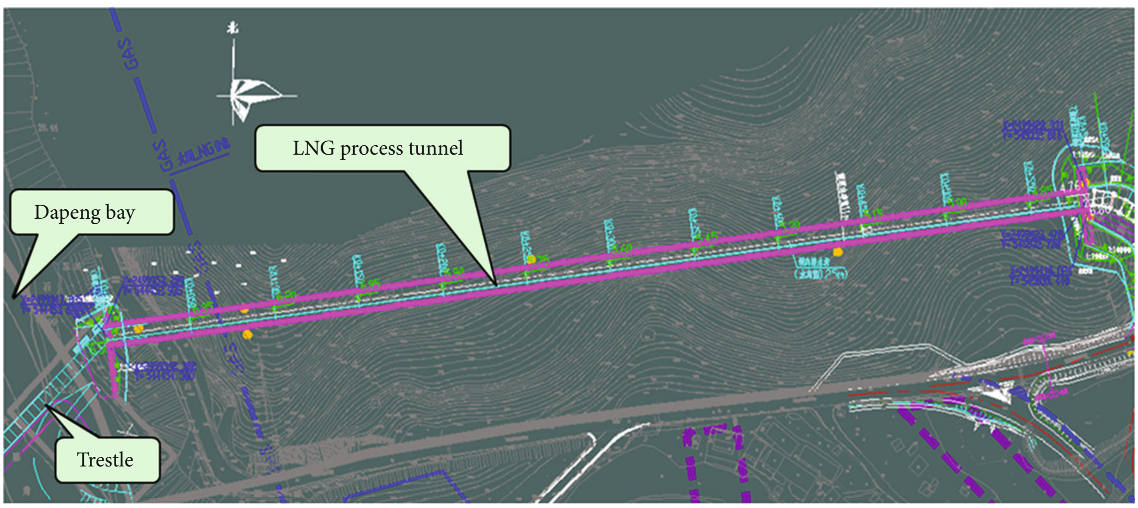


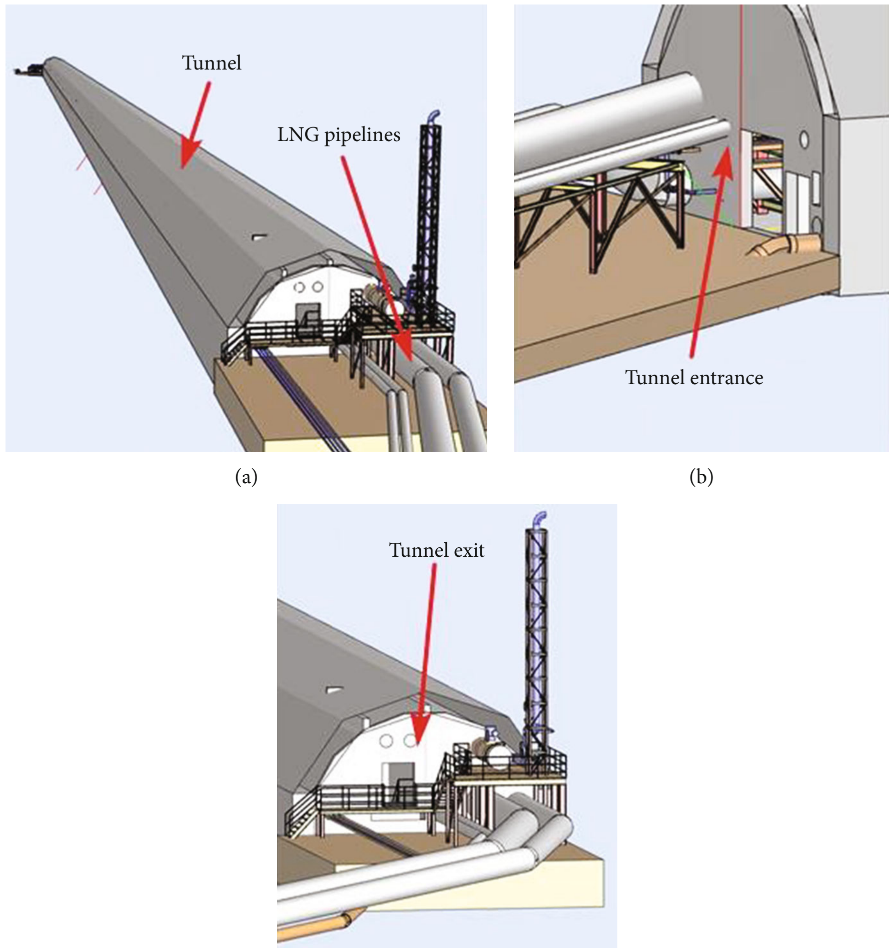
Figure 3: Layout plan of Shenzhen tunnel for an LNG pipeline.

direction) along the center of the LNG tunnel, the end surface of mechanical vent inlet is taken as measuring point 1, with spacing of 20 m between measuring points and a distribution length of 660 m.

4. Numerical Simulation and Analysis on LNG Diffusion

4.1. Analysis on LNG Leakage and Diffusion. According to the established numerical model of LNG pipeline within the tunnel, LNG leakage and diffusion are simulated on Case 1, Case 2, and Case 3, respectively [18]. The distribution cloud chart of contours of concentration (mass fraction) of CH_4 in the central longitudinal section of the tunnel at different time periods after LNG leakage and diffusion in Case 1 is as shown in Figure 6. The distribution law of CH_4 concentration in the LNG leakage tunnel in each time period in Case 1 is as shown in Figure 7. Figure 7 shows that CH_4 concentration is still relatively high in most parts of the tunnel after 5 minutes of LNG leakage and diffusion, only that in the 40 m long area upstream of the leakage source to the end surface of the tunnel remains lower than 1.7%. 10 minutes later, the LNG in the high concentration area is gradually discharged outward, while the low concentration area begins to expand, with a concentration less than 1.7% within the length of 150 m started from the tunnel along the path of the mechanical inlet. 15 minutes later, with further enlarged low concentration area, nearly 300 m long tunnel area is seeping into a rate lower than 1.7%—almost half of the total length. 20 minutes later, most parts in the tunnel have a concentration rate lower than 1.7%, except for a certain high concentration in front of the vents. 25 minutes later, as the average rate of concentration inside is less than 2.4%, CH_4 concentration field tends to be stable since the high concentration CH_4 has been discharged completely from the tunnel, and the flow field state inside does not change significantly. Since the leakage amount of LNG in Case 1 is relatively small, mechanical ventilation has become the main factor affecting the CH_4 concentration field in the tunnel. Under the effect of mechanical ventilation, the LNG leaked from the pipeline will flow out of the tunnel quickly along the pipeline after gasification. After the flow field in the tunnel is stable, the CH_4 concentration is very low, and the possibility of explosion is relatively small.

It can be seen from Figure 8 that the changing law of the CH_4 concentration field in Case 2 is similar to that of Case 1.



(c)

Figure 4: 3D model of Shenzhen tunnel for an LNG pipeline.

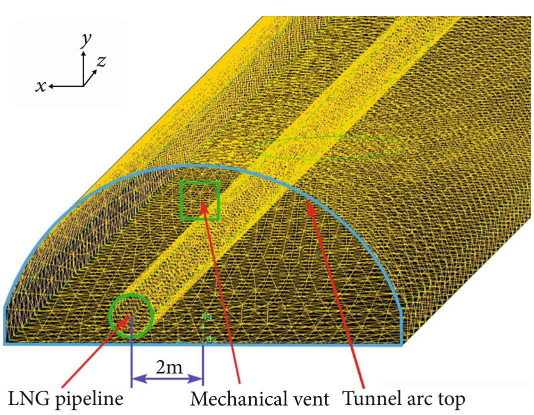


Figure 5: Grids for tunnel LNG pipeline simulation.

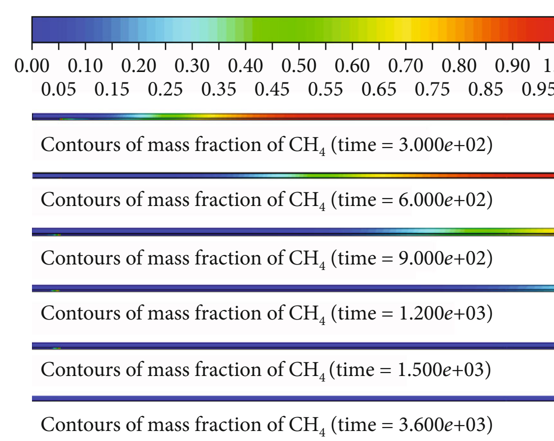


Figure 6: CH_4 concentration contours of the tunnel central longitudinal section.

The difference is that the leakage of LNG in Case 2 has greatly increased, and the effect of mechanical ventilation has been weakened. At the same time, the concentration of CH_4 at the same location of the tunnel is higher than that of Case 1, and the dilution rate of CH_4 is also significantly slowed down. After LNG leaked and diffused for 5 minutes, the CH_4 concentration was higher in most locations in the tunnel; only the CH_4 concentration in the 25 m long area from the front of the leak source to the tunnel end was lower than 1.7%. After 10 minutes, the low CH_4 concentration area gradually expanded, but the expansion speed was significantly slower than that of Case 1. The CH_4 concentration

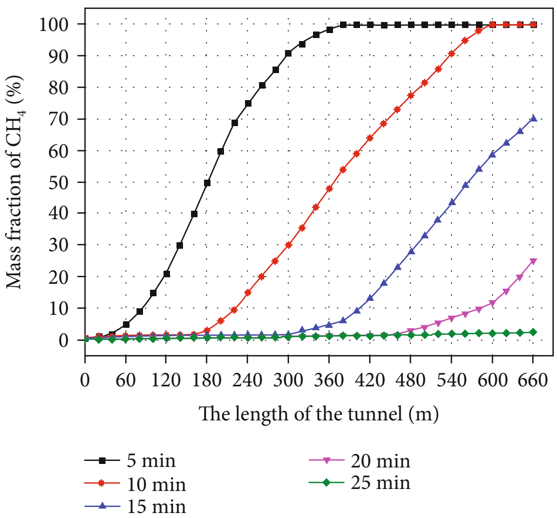


FIGURE 7: CH_4 concentration distribution in the tunnel (Case 1).

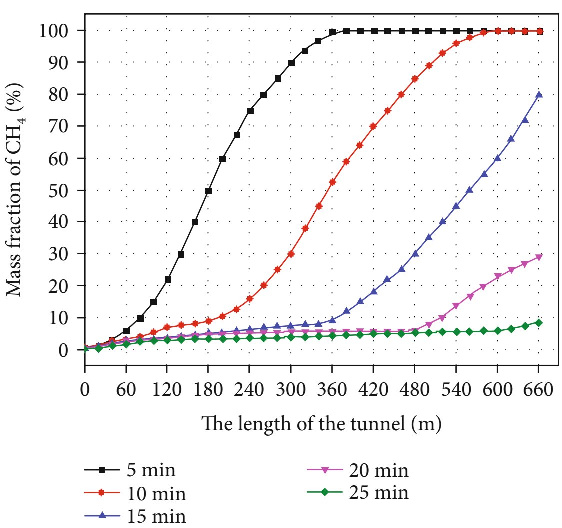


FIGURE 8: CH_4 concentration distribution in the tunnel (Case 2).

within 100 m from the end of the mechanical vent was below 5.0%. 15 minutes later, the low CH_4 concentration area continued to expand, and within 200 m from the end of the mechanical vent, the CH_4 concentration was below 5.0%. 20 minutes afterwards, the CH_4 concentration in most of the tunnel dropped to between 5.0% and 6.7%, and only a certain amount of high-concentration CH_4 gas cloud existed in the area in front of the tunnel exhaust. After 25 minutes of LNG leakage, the CH_4 concentration in most areas of the tunnel was between 3.0% and 5.0%, the CH_4 concentration field in the tunnel tended to be stable, and there was no significant change in the flow field state.

It can be seen from Figure 9 that the change trend of the CH_4 concentration field in Case 3 is similar to that of Case 1 and Case 2, but the increase rate of CH_4 concentration in the tunnel in Case 3 is faster than Case 1 and Case 2 in the same time period (Figure 10), and the effect of mechanical ventilation is significantly weakened. After 5 minutes of LNG leak-

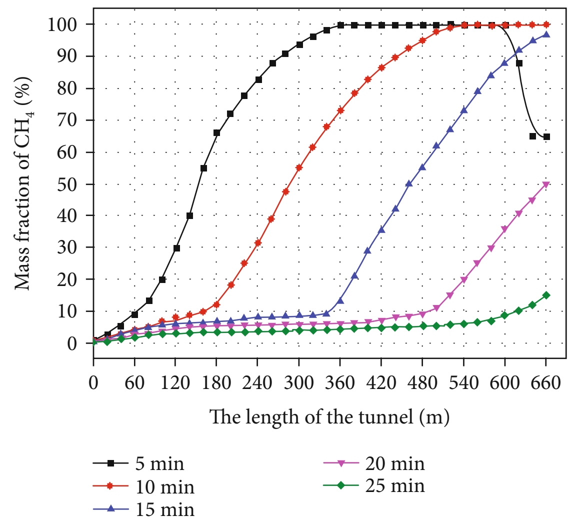


FIGURE 9: CH_4 concentration distribution in the tunnel (Case 3).

age, the high-concentration CH_4 distribution area has not been discharged from the tunnel. Most areas in the tunnel are filled with high concentration of CH_4. Due to the large amount of LNG leakage, the CH_4 discharge is slow, which causes the accumulation of CH_4 in the tunnel in a short time. However, the concentration of CH_4 at the exhaust outlet of the tunnel is relatively low, which shows that the CH_4 concentration distribution curve after 5 minutes decreases at the exit of the tunnel. After 10 minutes, the CH_4 concentration in the 100 m area before one end of the mechanical vent is lower than 6.7%, and most areas in the tunnel were still filled with high concentration of CH_4. 15 minutes later, from the source of the leak, the CH_4 concentration in most of the area 200 m along the direction of the wind is between 5.0% and 6.7%, and the air with high concentration of CH_4 continues to be discharged from the tunnel. After 20 minutes, the CH_4 concentration in most areas of the tunnel was between 5.0% and 6.7%, except for a high concentration of CH_4 gas cloud about 160 m long in front of the tunnel's air outlet. After 25 minutes, the CH_4 concentration in most areas of the tunnel is below 6.7%, the high-concentration CH_4 in front of the tunnel's air outlet had been exhausted, and the CH_4 concentration field in the tunnel is basically stable.

In order to further reflect the increasing rate of CH_4 concentration under different leakage volume in the same time period, the CH_4 concentration values after 5 min, 10 min, 15 min, and 20 min of LNG leakage at 120 m, 240 m, 360 m, and 480 m in the tunnel are, respectively, selected to form a histogram (Figure 10). It can be seen from Figure 10 that at the same location and time in the tunnel, the CH_4 concentration in Case 3 is higher than Case 2, and the CH_4 concentration in Case 2 is higher than Case 1, that is, the greater the leakage of LNG in the tunnel, the faster the increase in CH_4 concentration. This is a common phenomenon.

4.2. Distribution of CH_4 Explosion Gas Cloud in the Tunnel. When CH_4 concentration in the tunnel is higher than CH_4 explosion limit (volume fraction 5.3%-15.1% or mass fraction 2.82%~8.87%) [19], there is no explosion risk. However,

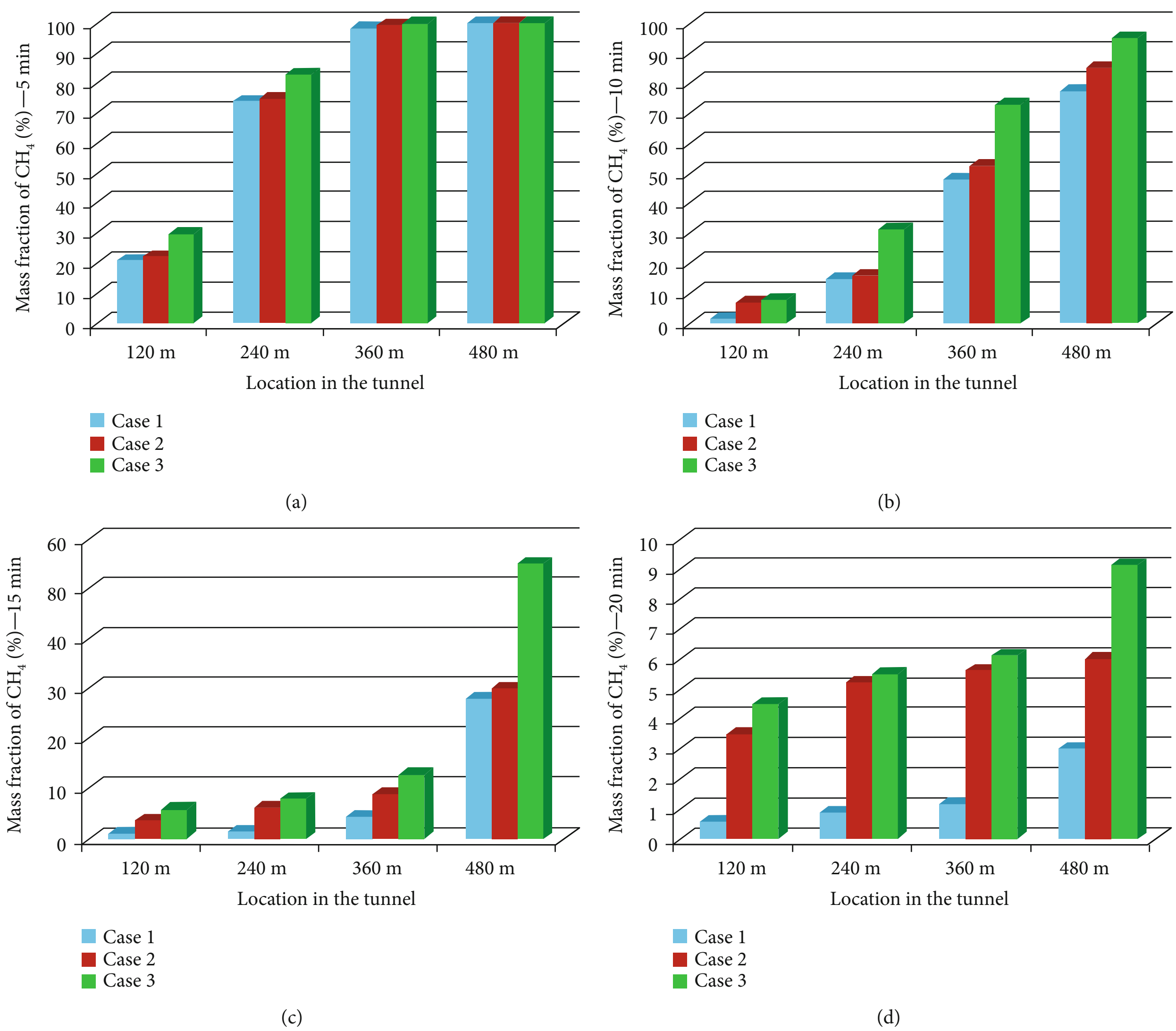


FIGURE 10: Increasing trend of CH_4 concentration in the tunnel (a) 5 min, (b) 10 min, (c) 15 min, and (d) 20 min.

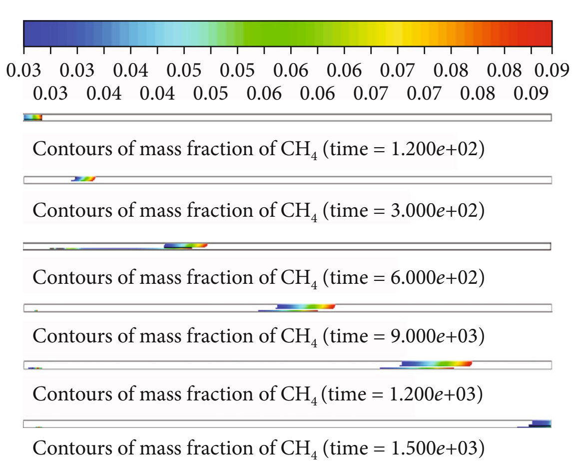


FIGURE 11: Simulation of CH_4 explosion cloud of tunnel central longitudinal section (Case 1).

with the continuous diffusion of CH_4 and when the mass fraction of CH_4 reaches 2.82%~8.87%, the CH_4 explosion gas cloud will be formed in the tunnel and will easily trigger an explosion by fire, which will be very dangerous. According to the numerical model of the LNG tunnel established in Figure 5, the distribution range of the explosion gas cloud after the LNG leak is simulated [20, 21]. Figure 11 shows the simulation results of the distribution range of the CH_4 explosion gas cloud in the longitudinal section of the tunnel center at different time periods after LNG leakage and diffusion in Case 1. It can be seen from Figure 11 that under the action of mechanical ventilation, the CH_4 explosion gas cloud moves constantly from the LNG leakage point to the tunnel exit, along with the constant change of the distribution length of the CH_4 explosion gas cloud.

According to the numerical simulation results of Case 1 (Figure 12), when the LNG pipeline leaked for 2 minutes, the CH_4 explosion gas cloud appears at the LNG leaking end of the tunnel with a length of about 30 m. After 5 minutes, the CH_4 explosion gas cloud moves to the other side

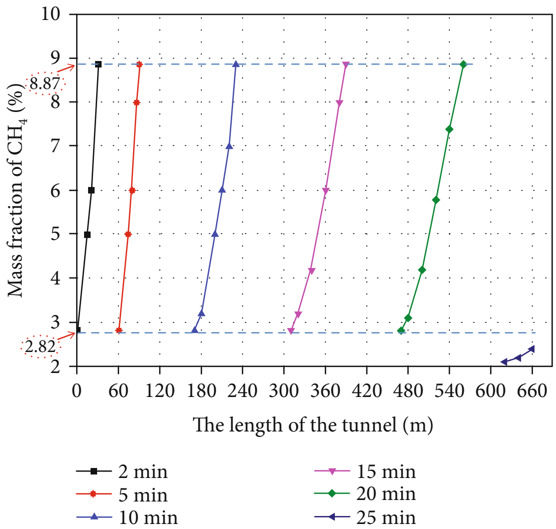


Figure 12: CH_4 explosion cloud distribution in the tunnel (Case 1).

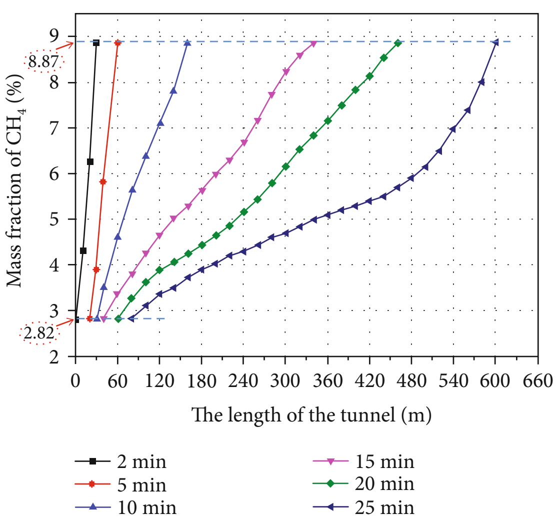


Figure 13: CH_4 explosion cloud distribution in the tunnel (Case 2).

of the tunnel at a speed of about 30 m/min under the action of mechanical ventilation, but the length did not increase. After 10 minutes, the CH_4 explosion gas cloud keeps moving along the wind, and there was a tendency to increase in length. After 20 minutes, the CH_4 explosion gas cloud approached the tunnel wind outlet and its length increased to 100 m. After 25 minutes, there is no CH_4 explosion gas cloud that was detected within 40 m from the tunnel wind outlet, which shows the CH_4 explosion gas cloud has moved out and no potential explosive risk caused by LNG leakage since the CH_4 concentration in the tunnel is lower than the explosion limit range.

The numerical simulation result of the CH_4 explosion gas cloud distribution of Case 2 is shown in Figure 13. Similar to Case 1, the CH_4 explosion gas cloud in Case 2 is formed in 2 minutes after LNG leakage. It appears at the mechanical wind inlet, with a length of around 30 m. 10 minutes later, the CH_4 explosion gas cloud keeps expanding to a length of about 180 m. 15 minutes later, from the mechanical vent, an area more than 300 m long in the tunnel is overwhelmed with CH_4 gas within the explosion limit. 25 minutes later, the entire tunnel is filled with CH_4 explosion gas cloud, which is extremely risky.

The simulation result of CH_4 explosion gas cloud distribution of Case 3 is shown in Figure 14. In Case 3, the CH_4 explosion gas cloud still appears 2 minutes after LNG leakage and the change trend is similar to the previous one, but the CH_4 concentration increases faster. 10 minutes later, the CH_4 explosion gas cloud starts to move along the wind, stretching its length till about 130 m. 15 minutes later, the CH_4 explosion gas cloud starts to fill the area of 40 m~340 m to the mechanical vent. 20 minutes later, the area covered by the CH_4 explosion gas cloud in the tunnel increases to 400 m with a constantly rising concentration. 25 minutes later, the CH_4 explosion gas cloud length has grown into over 540 m; massive explosion can happen at any time by fire. Due to the large amount of leakage in Case 3, the spreading speed is relatively slow; yet, the CH_4 concentration at the vent is still relatively high. Therefore, there is no CH_4 explosion gas cloud within the area about 60 m to the tunnel wind outlet.

4.3. Influence of Location of LNG Leakage Point to CH_4 Diffusion. Take the leakage of LNG in Case 2 as an example. The place at 360 m of the tunnel center is taken as the measuring point to study the influence of location of LNG leakage point on CH_4 concentration at the measuring point through numerical simulation; the simulation result is shown in Figure 15. It can be seen from Figure 15 that CH_4 concentration decreases as the leakage point shifts from the end of the tunnel wind inlet to the wind outlet when the leakage point is located in front of the measuring point (close to the wind inlet). CH_4 concentration at the leakage point is barely zero when the leakage point is located behind the measuring point (close to the wind outlet). The analysis results can be generalized as follows: if the leakage point is located near the wind inlet, most of the space in the tunnel will be filled with CH_4, and as CH_4 diffuses slowly, making it difficult to discharge CH_4; if the leakage point is located far from the wind inlet, there will be no diffusion of CH_4 in front of the leakage point and it spreads quickly behind the leakage point, making it easier to discharge CH_4.

According to the above simulation analysis, in order to prevent the occurrence of natural gas combustion or explosion in the LNG technical tunnel, the researchers suggest that the LNG technical tunnel should be filled with nitrogen and sealed. The purpose of filling with nitrogen is to prevent the occurrence of natural gas combustion or explosion for there is almost no oxygen in the tunnel when LNG leakage occurs in the tunnel, so as to completely solve the safety problem of LNG technical tunnel. The Shenzhen LNG process tunnel engineering project department has completed the water-tightness and air-tightness experiments of nitrogen injection in the tunnel and then performed nitrogen replacement, that is, nitrogen is injected from one end of the tunnel while air is exhausted until the gas sampling analysis in the tunnel has a water dew point of -20°C, indicating that the nitrogen has

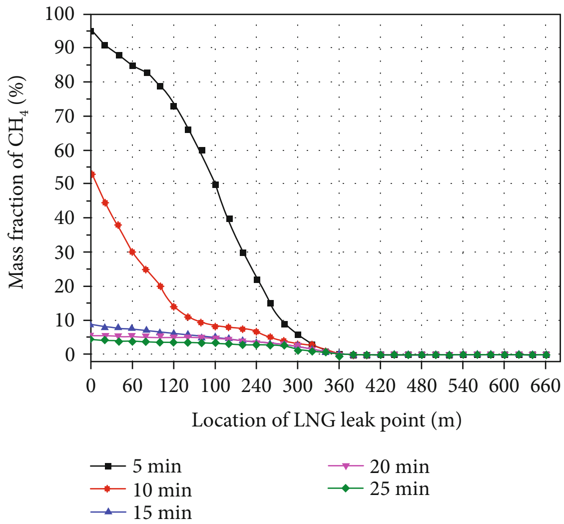


FIGURE 15: Effect of LNG leak location on CH_4 diffusion.

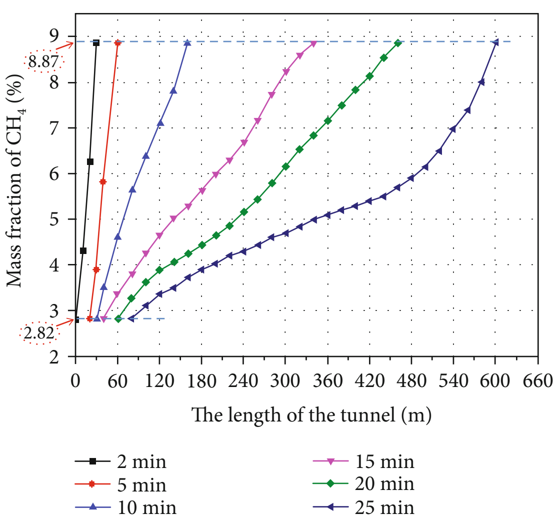


FIGURE 14: CH_4 explosion cloud distribution in the tunnel (Case 3).

been replaced and the air in the tunnel has been exhausted. Then, close the exhaust port and continue to inject nitrogen. When the nitrogen pressure in the tunnel reaches 3 kPa (slightly positive pressure), the nitrogen injection can be stopped. Under normal operating conditions, the LNG process tunnel is in a fully sealed state with high concentration of nitrogen inside. In this state, there is no oxygen in the tunnel, so even if natural gas leaks, it will not cause combustion or explosion.

5. Conclusions

(1) Through the numerical simulation of the leakage and diffusion process of the LNG pipeline within the tunnel, it can be seen that the mechanical ventilation becomes the key factor influencing the CH_4 concentration field in the tunnel due to the relatively small amount of LNG leakage in Case 1 within the same time period. The increase rate of CH_4 concentration in Case 3 is faster than that in Case 1 and Case 2. The effect of mechanical ventilation is obviously weakened when the amount of LNG leakage in the tunnel is large

(2) The diffusion of CH_4 will be slower, and it will be difficult to be exhausted from the tunnel when the leakage point is located near the air inlet of mechanical ventilation of the tunnel. If the leakage point is located far away from the air inlet of mechanical ventilation of the tunnel, CH_4 diffusion is faster and it is easier to be exhausted from the tunnel

(3) The length of the CH_4 explosion gas cloud in Case 1 is relatively short and moves along with the wind, which will move out from the tunnel soon. The length of the CH_4 explosion gas cloud in both Case 2 and Case 3 increases fast with a dramatic trend of change, which could be extremely risky, and efforts should be made to prevent such accidents

Data Availability

The (data type) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C. Yue, L. Chen, H. Xiang et al., "Assessment of cascading accidents of frostbite, fire, and explosion caused by liquefied natural gas leakage," *Advances in Civil Engineering*, vol. 2020, Article ID 8867202, 14 pages, 2020.

[2] K. Wang, Y. He, Z. Liu, and X. Qian, "Experimental study on optimization models for evaluation of fireball characteristics and thermal hazards induced by LNG vapor cloud explosions based on colorimetric thermometry," *Journal of Hazardous Materials*, vol. 366, pp. 282–292, 2019.

[3] S. Dan, C. J. Lee, J. Park, D. Shin, and E. S. Yoon, "Quantitative risk analysis of fire and explosion on the top-side LNG-liquefaction process of LNG-FPSO," *Process Safety and Environmental Protection*, vol. 92, no. 5, pp. 430–441, 2014.

[4] J. Würtz, J. Bartzis, A. Venetsanos, S. Andronopoulos, J. Statharas, and R. Nijsing, "A dense vapour dispersion code package for applications in the chemical and process industry," *Journal of Hazardous Materials*, vol. 46, no. 2-3, pp. 273–284, 1996.

[5] P. H. Bottelberghs, “Risk analysis and safety policy developments in the Netherlands,” *Journal of Hazardous Materials*, vol. 71, no. 1-3, pp. 59–84, 2000.

[6] D. Lv, W. Tan, L. Liu, G. Zhu, and L. Peng, “Research on maximum explosion overpressure in LNG storage tank areas,” *Journal of Loss Prevention in the Process Industries*, vol. 49, pp. 162–170, 2017.

[7] J. Hu, R. Wang, and L.-b. Zhang, “Topological network inversion method of fire source location for liquefied natural gas (LNG) storage,” *Procedia Engineering*, vol. 211, pp. 247–255, 2018.

[8] S. Ren, “The leakage, low temperature diffusion and explosion of liquefied natural gas in open space,” *Explosion and Shock Waves*, vol. 38, pp. 891–897, 2018.

[9] T. Baalisampang, R. Abbassi, V. Garaniya, F. Khan, and M. Dadashzadeh, “Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG,” *Process Safety and Environmental Protection*, vol. 128, pp. 259–272, 2019.

[10] Z. Li, J. Wu, M. Liu, Y. Li, and Q. Ma, “Numerical analysis of the characteristics of gas explosion process in natural gas compartment of utility tunnel using FLACS,” *Sustainability*, vol. 12, no. 1, p. 153, 2020.

[11] L. Chaoyang, G. Ma, and L. Xu, “Numerical study on diffusion concentration of overhead and buried natural gas pipeline,” *Journal of Safety Science and Technology*, vol. 7, no. 7, pp. 66–69, 2011.

[12] Y. H. Dong, H. L. Gao, J. E. Zhou, and Y. Feng, “Mathematical modeling of gas release through holes in pipelines,” *Chemical Engineering Journal*, vol. 92, no. 1-3, pp. 237–241, 2003.

[13] B. R. Cormier, R. Qi, G. W. Yun, Y. Zhang, and M. Sam Mannan, “Application of computational fluid dynamics for LNG vapor dispersion modeling: a study of key parameters,” *Journal of Loss Prevention in the Process Industries*, vol. 22, no. 3, pp. 332–352, 2009.

[14] Y. D. Jo and B. J. Ahn, “A simple model for the release rate of hazardous gas from a hole on high-pressure pipelines,” *Journal of Hazardous Materials*, vol. 97, no. 1-3, pp. 31–46, 2003.

[15] S. Yaobin, L. Weiyong, H. Changchun, and B. Erhu, “Numerical simulation of the influence of natural fractures on hydraulic fracture propagation,” *Geofluids*, vol. 2020, Article ID 8878548, 12 pages, 2020.

[16] K. H. Sung, J. W. Bang, L. Li et al., “Effect of crack size on gas leakage characteristics in a confined space,” *Journal of Mechanical Science and Technology*, vol. 30, no. 7, pp. 3411–3419, 2016.

[17] L. Li, J. Choi, J. Bang, S. Lee, S. H. Lee, and D. Kim, “Numerical investigation of LNG gas dispersion in a confined space: an engineering model,” *Journal of Mechanical Science and Technology*, vol. 31, no. 9, pp. 4533–4540, 2017.

[18] D. Zhu, “Example of simulating analysis on LNG leakage and Dispersion,” *Procedia Engineering*, vol. 71, pp. 220–229, 2014.

[19] G. Dong, L. Xue, Y. Yang, and J. Yang, “Evaluation of hazard range for the natural gas jet released from a high-pressure pipeline: a computational parametric study,” *Journal of Loss Prevention in the Process Industries*, vol. 23, no. 4, pp. 522–530, 2010.

[20] E. Kim, J. Park, J. H. Cho, and I. Moon, “Simulation of hydrogen leak and explosion for the safety design of hydrogen fueling station in Korea,” *International Journal of Hydrogen Energy*, vol. 38, no. 3, pp. 1737–1743, 2013.

[21] Y. Liu, Z. Qiu, H. Zhong et al., “Bitumen recovery from crude bitumen samples from Halfaya oilfield by single and composite solvents-process, parameters, and mechanism,” *Materials*, vol. 12, no. 17, p. 2656, 2019.