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Theoretical and Numerical Analysis of Liquefied Natural Gas Leakage and Dispersion

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ABSTRACT: Liquefied Natural Gas (LNG) is a clean and efficient energy source; however, due to its high flammability and explosive potential, accidental releases can lead to severe fire and explosion hazards as well as environmental damage and casualties. To evaluate and enhance the predictive capability of dispersion models, the accuracy of the Phast™ software was validated using experimental data from the Falcon series, i.e., five large-scale (up to 66 m³) pressurized LNG release tests originally conducted by the Lawrence Livermore National Laboratory (LLNL). Using Phast™, we systematically investigated the effects of key environmental and operational parameters, including leak size, release angle, wind speed, atmospheric stability, surface roughness, and ambient temperature, on the dispersion behavior of LNG vapor clouds. The results indicate that leak size primarily determines the release rate and the initial volume of the gas cloud, thereby influencing its overall dispersion range. The release angle strongly affects the morphology of the vapor cloud, with smaller angles producing longer downwind dispersion distances. Wind speed exhibits a nonlinear influence: at lower velocities, incremental increases in wind speed lead to a marked extension of the dispersion range. Under highly stable atmospheric conditions, the vapor tends to spread predominantly downwind, enhancing the longitudinal reach of the cloud. Conversely, in less stable or turbulent atmospheres, enhanced vertical mixing shortens the horizontal spread. Increased surface roughness reduces both the velocity and extent of dispersion, while higher ambient temperatures accelerate LNG vaporization, thereby expanding the overall dispersion area.

KEYWORDS: LNG; Phast; leakage dispersion; numerical simulation

1 Introduction

The LNG industry plays a vital role in improving the energy structure, promoting environmental protection, and driving economic growth. However, accidental LNG releases can generate flammable vapor clouds, posing serious risks to people and property [1,2]. According to the IEA, natural gas demand is expected to grow into the 2030s, and natural gas may overtake coal as the world's second-largest energy source around 2030 [3]. The China Urban Statistical Yearbook 2020 reports a 96% urban natural gas coverage rate, reflecting the extensive utilization of LNG. In 2019, China imported 133.253 billion cubic meters of LNG, accounting for 43.4% of its total natural gas consumption—surpassing South Korea and Japan to become the world's second-largest LNG importer [4]. Therefore, understanding LNG vapor-cloud release and dispersion under representative conditions is essential for risk assessment and safety design. Such

understanding supports the determination of safety distances and design criteria for terminal design, site selection, and storage-tank layout.

Numerical simulation is widely used to study LNG releases and atmospheric dispersion, allowing the dispersion process to be reproduced under controlled conditions. However, phase-changing dispersion is difficult to model because the near-field two-phase release is complex, especially in wind-tunnel experiments; therefore, the initial release stage is often simplified [5]. While these simplifications improve model tractability, they may limit the fidelity of the simulation in capturing real-world leakage dynamics, potentially affecting the accuracy of the numerical results [6–8]. Xie et al. [9] proposed a quantitative method for assessing the fire and explosion hazards associated with LNG fuel leakage incidents in ship elevators, focusing on risks to personnel and structural integrity. Lim et al. [10,11], drawing on INERIS research and the Isenthalpic Homogeneous Equilibrium Model, developed a model for flashing LNG leaks and compared safety information models for LNG refueling zones with FLACS simulations to estimate safe operational boundaries during ferry refueling. Li et al. [12] combined phase equilibrium principles with the Gaussian plume model to analyze the characteristics of three critical stages in large-scale LNG tank leaks: jet release, pool evaporation, and vapor cloud dispersion. Chen et al. [13] employed mathematical analysis to identify dynamic risk factors in natural gas pipeline networks, aiming to assess the hazards of natural gas usage in semi-enclosed mountainous urban terrains. Using an LNG storage tank at a storage and distribution station as a case study, You et al. [14] examined the effects of leak-orifice size and wind speed on the downwind dispersion distance of an LNG vapor cloud and the associated jet-fire and explosion hazard ranges. Tang et al. [15] investigated the leakage modes of a vertical jet source and the dispersion behavior under different environmental conditions.

Due to the diverse physical properties of hazardous substances and the variability of their application environments, there is currently no academic consensus on which turbulence model is most suitable for simulating gas dispersion phenomena in specific spatial settings [16]. Therefore, model validation for LNG releases under representative meteorological and surface conditions remains necessary. In this study, numerical simulations were conducted using the Phast™ software, which allows for the modeling of multiple leak sources and various weather conditions to simulate the dispersion trajectories and maximum impact zones of flammable or toxic gases. These simulations provide critical support for disaster consequence mitigation and the optimization of engineering design. By employing appropriate scientific methods to investigate the dispersion behavior of LNG in detail, it becomes possible to implement rapid and accurate response strategies during the initial stages of a leak, thereby significantly reducing the risk and severity of potential fire and explosion incidents. This study conducts a systematic parametric sensitivity analysis that covers leak angle, orifice size, wind speed, Pasquill–Gifford stability class, surface roughness, and ambient temperature, and it characterizes the non-monotonic behavior of ERPG exceedance distance and lateral spread. The findings of this study hold substantial theoretical value and practical significance for guiding and improving the safety management and operational mechanisms of LNG storage and transportation. Moreover, they provide a theoretical foundation for controlling LNG dispersion and designing safer LNG receiving terminals.

2 Fundamental Modeling Framework of Phast

2.1 UDM Model

The Unified Dispersion Model (UDM), implemented in the Phast™, is widely used for consequence modelling of accidental releases. This model accounts for multiple factors, including jet release, gravity, buoyancy, and atmospheric dispersion, as well as droplet formation, liquid pool development, and subsequent

pool evaporation [17]. Designed primarily for consequence and risk assessment studies, the UDM is capable of simulating downwind dispersion following two-phase pressurized flashing releases. It covers all phases of dispersion in both near-field and far-field regions, including droplet deposition and the resulting liquid pool formation and evaporation. For post-deposition dispersion, the model assumes a uniform surface roughness over flat terrain to facilitate the calculation of the subsequent dispersion extent [18].

The UDM is also capable of modeling plume lift-off, wherein ground-level gas clouds rise due to buoyancy; such uplifted plumes may become confined within the atmospheric mixing layer. The model supports various dispersion scenarios, including continuous, instantaneous, steady-state, finite-duration, and time-varying releases. In low wind speed conditions, the UDM incorporates gravity-driven downwind dispersion effects. For time-dependent dispersion, the model also accounts for wind-influenced transport. When dealing with multicomponent gas mixtures, the UDM can employ a pseudo-component approach to simplify the simulation. Alternatively, if a liquid pool is present but detailed modeling is unnecessary, the model allows for the use of a more rigorous multi-component formulation for improved accuracy.

In the case of continuous heavy gas release, Fig. 1 illustrates the distinct phases of downwind dispersion: the jet phase, the transition phase, and the atmospheric dispersion phase. The dispersion process initially begins with the jet phase, followed by a transitional phase, and finally evolves into full atmospheric dispersion. The transition phase is introduced to ensure continuity between the near-field and far-field dispersion regimes, preventing abrupt changes in dispersion behavior.

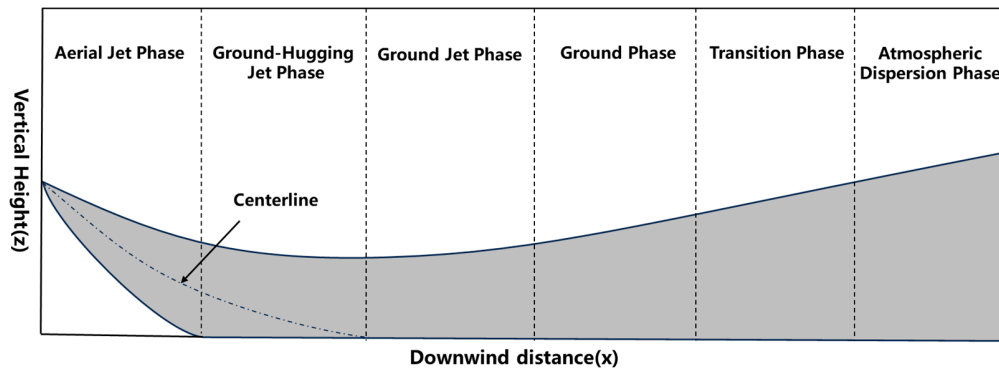


Figure 1: Different dispersion stages of the UDM.

Jet entrainment is driven by the velocity difference between the jet and the ambient wind. It occurs both when the plume velocity exceeds the surrounding wind speed (jet regime) and when it is lower than the ambient wind speed (plume regime). The entrainment rate is proportional to the coefficient α_1 , and is expressed by the following equation:

$$E_{jet} = (0.5\pi^{-0.5}\alpha_1)P_{above}\rho_a|u_{cld} - u_a\cos\theta| \quad (1)$$

where,

- E_{jet} is the jet entrainment rate (kg/s or kg/m/s)
- P_{above} is the perimeter of the plume cross-section (m)
- u_a is the ambient wind speed (m/s)
- u_{cld} is the velocity of the gas cloud (m/s)
- θ is the angle between the plume and the horizontal
- ρ_a is the ambient air density (kg/m³)

- α_1 is the jet entrainment coefficient (mol/m^3)

For continuous releases, E_{jet} represents the entrained mass per unit length along the plume center-line, and P_{above} denotes the total entrainment perimeter. In such cases, P_{above} can be replaced with the instantaneous equivalent plume area above the ground (S_{above}) for simplification.

Crosswind entrainment is associated with the formation of wake vortices, which arise from the deflection of the released plume by the ambient air, leading to the development of upward or downward moving wake flows. This entrainment process is proportional to the coefficient α_2 . For continuous dispersion, the crosswind entrainment rate can be expressed as:

$$E_{cross} = \alpha_2 P_{above} \rho_a |u_a \sin \theta| \quad (2)$$

where,

- E_{cross} is the crosswind entrainment rate (kg/s or kg/m/s)

The formulation for crosswind entrainment in instantaneous releases is derived from the equation used for continuous dispersion. In this case, the plume perimeter P_{above} is replaced by the plume cross-sectional area S_{above} .

Lateral passive entrainment is induced by ambient turbulence and is defined as follows:

$$E_{pas}^{nf} = \left[1 - \frac{W_{gnd}}{R_y} \right] \pi \rho_a e_{pas} \epsilon^{1/3} (l_y^{4/3} + l_z^{4/3}) \quad (3)$$

where,

- E_{pas}^{nf} is the near-field passive entrainment rate (kg/s or kg/m/s)
- W_{gnd} is the semi-continuous plume width near the ground (m)
- y is the crosswind distance (m)
- R_y is the lateral concentration profile width (m)

For continuous dispersion scenarios, the value of e_{pas} is taken as 1. The turbulent length scales in the horizontal l_y and vertical l_z directions, as well as the turbulence dissipation rate (ϵ), are defined as follows:

$$l_y = \min \{ R_y, 0.88(z_c + z_o) L_y(Z) \} \quad (4)$$

$$l_z = \min \{ R_y, 0.88(z_c + z_o) L_z(Z) \} \quad (5)$$

$$\epsilon = E(z_c + z_o/L) u^3 / [\kappa(z_c + z_o)] \quad (6)$$

where,

- z_c is the centroid height (m)
- z_o is the surface roughness length (m)
- L is the Monin-Obukhov length (m)
- u is the friction velocity (m/s)
- κ is the von Kármán constant
- $L_y(Z)$, $L_z(Z)$ and $E(Z)$ are atmospheric stability functions

2.2 ATEX Model

The Atmospheric Expansion Model (ATEX) is used to calculate the expansion of a continuous release from a leak point (or pipe outlet) into the atmosphere. Based on specified initial conditions, the ATEX model computes the final conditions at the end of the expansion process. As illustrated in Fig. 2, the final conditions include five key parameters: the expanded area A_f , velocity u_f , temperature T_f , liquid fraction f_{Lf} , specific volume $v_f = (1/\rho_f)$, and specific enthalpy h_f . These final expansion parameters serve as the input conditions for the UDM dispersion model. The ATEX framework incorporates two sub-models to simulate the expansion process into the atmosphere: the Energy Conservation model, which assumes momentum conservation, and the Isentropic model, which assumes entropy conservation [19].

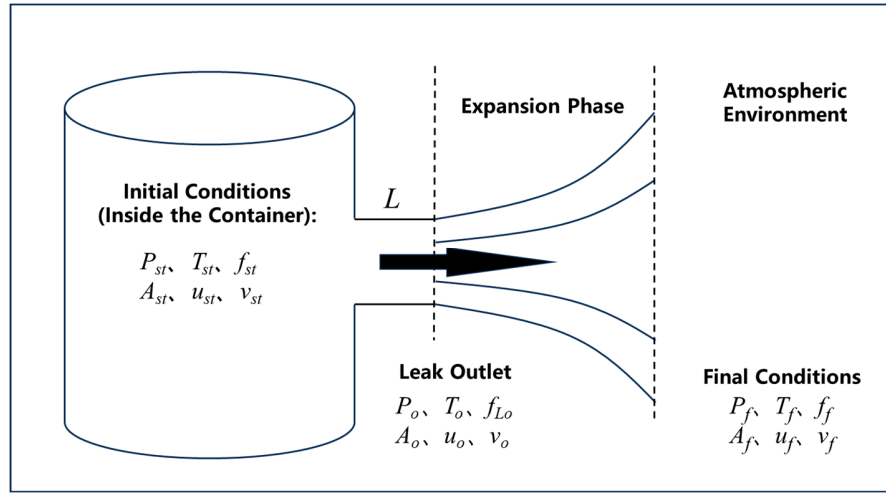


Figure 2: Different stages of atmospheric expansion.

The final expansion parameters are derived from the initial conditions using three conservation equations—mass conservation, momentum conservation, and energy conservation—along with two state equations: density continuity and enthalpy continuity.

$$\rho_f A_f u_f = \rho_o A_o u_o \quad (7)$$

$$\rho_f A_f u_f^2 = \rho_o A_o u_o^2 + (P_o - P_f) A_o \quad (8)$$

$$\frac{\rho_f A_f u_f}{\rho_o A_o u_o} = \frac{[h_o(P_o, T_o; f_{Lo}) + \frac{1}{2} u_o^2]}{[h_f + \frac{1}{2} u_f^2]} \quad (9)$$

$$\rho_f = \rho_f(P_a, T_f; f_{Lf}) \quad (10)$$

$$h_f = f_{Lf} h_f(P_a, T_f) + (1 - f_{Lf}) h_v(P_a, T_f) \quad (11)$$

where,

- h is the specific enthalpy (J/kg)
- A is the jet cross-sectional area (m²)
- ρ is the density (kg/m³)

- u is the velocity (m/s)
- T is the temperature ($^{\circ}\text{C}$)
- f is the liquid mass fraction

The isentropic model uses the same set of equations as the previously described model. However, unlike the energy conservation model—which assumes momentum conservation—the isentropic model assumes that entropy remains constant between the initial and final states. In other words, the entropy at the end of the expansion is equal to that at the leak outlet. The isentropic equation is expressed as:

$$s(T_o, P_o) = s(P_a, T_f; f_{Lf}) \quad (12)$$

where,

- s is the specific entropy (J/K/kg)

2.3 DISC Model

The DISC model is used to simulate both instantaneous and continuous leakage scenarios. Under a steady leak rate, the non-transient continuous model can predict the initial release rate and duration—typically representing a worst-case scenario. The DISC model consists of four sub-models: the orifice model, the short pipe model, the instantaneous release model, and the vapor release model. For all sub-models except the vapor release model, the ATEX model is subsequently used to simulate the expansion of the release to atmospheric conditions, as previously described. The orifice model simulates continuous (non-time-varying) releases through an orifice, assuming a constant initial release rate. It is designed to estimate the worst-case initial flow rate and the corresponding release duration. The phase of the material within the vessel may be vapor, liquid, or two-phase [20].

As illustrated in Fig. 3, the orifice model describes the transition from initial conditions to the conditions at the orifice. The pre-release or initialization conditions are determined based on the specific scenario and relevant parameters. The expansion from the orifice to atmospheric conditions is calculated using the ATEX model. The liquid density used in the calculation is taken from the top of the liquid column. The pre-release condition is computed using the following equation:

$$P_i = P_{st} + \rho_L(P_{st}, T_{st})g\Delta H \quad (13)$$

$$T_i = T_{st} \quad (14)$$

where,

- P_i is the pre-release pressure (Pa)
- P_{st} is the initial storage pressure (Pa)
- ρ_L is the liquid density (kg/m^3)
- g is the gravitational constant (m/s^2)
- ΔH is the hydraulic head (m)

The orifice conditions are determined using both the isentropic and isenthalpic equations, as given below:

$$h(P_i, T_i, \eta_{Li}) = h(P_o, T_o, \eta_{Lo}) + \frac{u_o^2}{2} \quad (15)$$

$$s(P_i, T_i, \eta_{Li}) = s(P_o, T_o, \eta_{Lo}) \quad (16)$$

where,

- η is the liquid mass fraction
- s is the specific entropy (J/K·kg)
- h is the specific enthalpy (J/kg)
- u is the velocity (m/s)

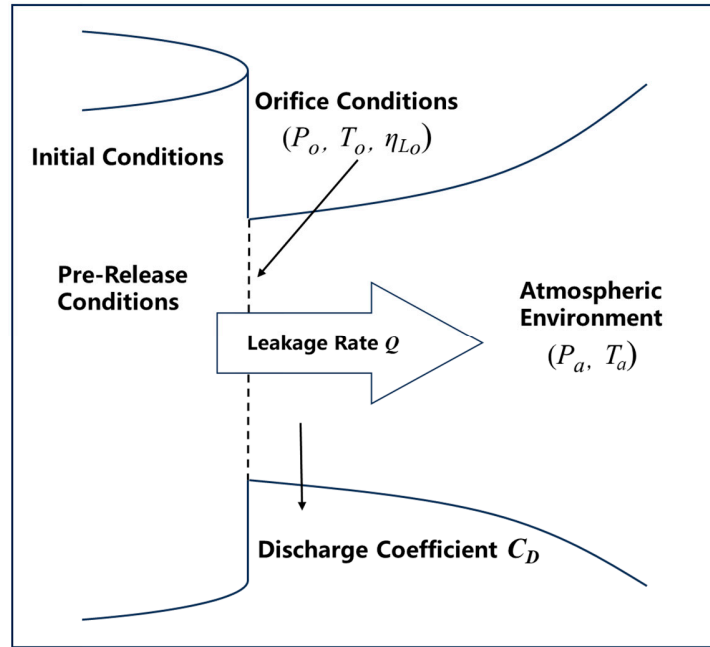


Figure 3: The orifice model.

The choked pressure at the orifice P_o is determined based on either the ambient pressure in the case of no obstruction or the choked pressure in the case of flow restriction. P_c represents the critical (choked) pressure at the orifice, defined as the pressure at which the mass flux G_o through the orifice reaches its maximum. The corresponding equation is as follows:

$$P_o = \max[P_a, P_c] \quad (17)$$

$$G_o = u_o/v_o \quad (18)$$

$$v_o = \frac{\eta_{Lo}}{\rho_{Lo}} + \frac{\eta_{Vo}}{\rho_{Vo}} \quad (19)$$

$$Q^* = A_o G_o \quad (20)$$

where,

- P_o is the choked (critical) pressure (Pa)
- Q^* is the mass release rate (kg/s)

- G_o is the mass flux at the orifice ($\text{kg}/\text{m}^2\cdot\text{s}$)
- A_o is the orifice cross-sectional area (m^2)

t_{rel} is the release duration, calculated as:

$$A_v = C_D A_o \quad (21)$$

$$Q = A_v G_o \quad (22)$$

$$t_{rel} = \frac{M_{st}}{Q} \quad (23)$$

where,

- Q is the mass flow rate (kg/s)
- M_{st} is the initial mass (kg)
- A_v is the effective discharge area (m^2)
- t_{rel} is the release duration (s)
- C_D is the discharge coefficient

The meanings of the parameter subscripts used in this study are summarized in Table 1.

Table 1: Parameter index annotations.

Subscript	Description	Subscript	Description
a	Atmospheric conditions	θ	Angle between plume and horizontal
f	Final conditions	st	Initial conditions
L	Liquid phase conditions	v	Vapor phase conditions
o	Leak outlet conditions	-	-

3 Assessment of Phast Model Predictions

3.1 Falcon Experiments

The Falcon experiments were a series of five large-scale (up to 66 m^3) pressurized LNG release tests conducted by the Lawrence Livermore National Laboratory (LLNL) for the U.S. Department of Transportation (DOT) and the Gas Research Institute (GRI) [21]. The primary objective of the Falcon experiments was to evaluate the effectiveness of bund mitigation during accidental LNG releases and to provide a data foundation for validating wind tunnel tests and numerical simulation models. The Falcon dataset is publicly available and well documented. It involves on-water LNG spills with vapour-fence and obstacle configurations representative of facility conditions. The trials span neutral to very stable atmospheric regimes (e.g., D to G in the PHMSA (Pipeline and Hazardous Materials Safety Administration) validation database) and have been used in model-evaluation/validation efforts as well as CFD benchmarking studies [22]. The liquefied natural gas was released into a rectangular pool measuring 60 m in length and 40 m in width. The pool was equipped with a circulation system to ensure that the evaporation rate closely matched the LNG release rate. LNG was delivered into the pool through four pipelines, each with a diameter of 110 mm, spaced 90 degrees apart to maximize the surface coverage of LNG on the water. (Fig. 4 shows the Falcon experiment release setup.) The bund surrounding the pool was 8.7 m high, enclosing a total area of 44 m by 88 m. In addition to the bund, a barrier structure—13.3 m high and 17.1 m wide—was placed upwind of the pool to simulate the effects of storage tanks or other obstructions on vapor cloud dispersion. The

terrain around the enclosure was flat, and the experiments were conducted under stable or moderately stable atmospheric conditions (Pasquill-Gifford stability classes D–F). The saturated vapor volume of the released LNG was less than the volume of water in the containment area.

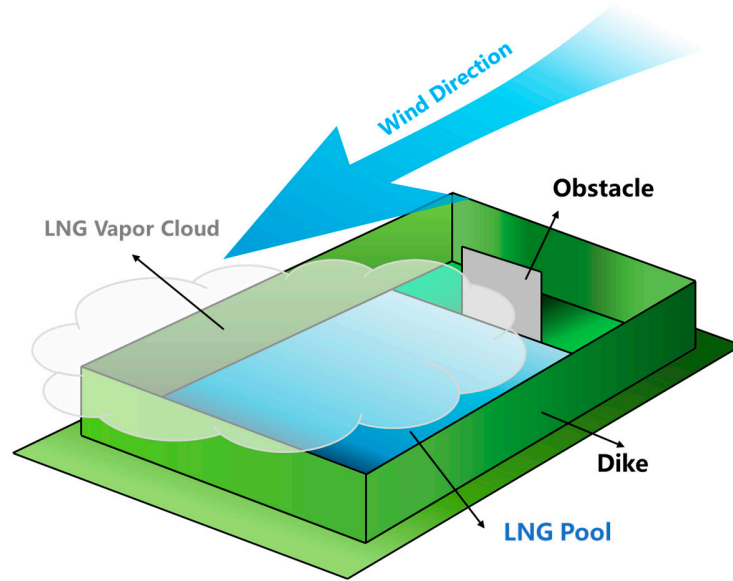


Figure 4: Diagram of the Falcon experimental site.

3.2 Validation of Phast Prediction Results

A total of five Falcon experiments were conducted, among which Falcon-1 featured the lowest wind speed (1.7 m/s), the largest release volume (66.4 m³), and the most stable atmospheric condition (stability class G). Under such stable atmospheric conditions, strong stratification inhibits the mixing of the plume with the surrounding air, limiting vertical dispersion and causing the gas to remain concentrated at lower altitudes [23]. The low wind speed in this scenario further reduced the dispersion rate, allowing natural gas concentrations to reach elevated levels within a confined area and increasing the extent of the region where the gas concentration exceeded the lower flammability limit (LFL). This configuration closely represents a worst-case scenario, which aligns with the objective of this study. Therefore, the Falcon-1 experimental conditions and data were selected for validating the Phast™ simulation results. Table 2 summarizes the parameters of the Falcon field trials.

Table 2: Parameters of the Falcon field trials.

	Falcon-1	Falcon-2	Falcon-3	Falcon-4	Falcon-5
Duration/s	131	78	154	301	78
release rate/m ³ ·min ⁻¹	28.7	15.9	18.9	8.7	30.3
Orifice diameter/mm	11.43	11.43	11.43	3.81	11.43
mass fraction	94.7	95.6	91	91	88
Average wind speed/m·s ⁻¹	1.7	4.7	4.1	5.2	2.8
Humidity/%	-	-	4	12	13.7
Stability class	G	D	D	D/E	E/F
Roughness length/m	0.008	0.008	0.008	0.008	0.008

Fig. 5 shows the layout of the concentration sensors used in the Falcon-1 experiment. Sensor arrays were installed at three downwind distances from the LNG pool: 50 m, 150 m, and 250 m. At the 50 m

downwind position, sensors were placed at crosswind offsets of 66 m, 44 m, 22 m, 0 m, −22 m, −44 m, and −66 m. At the 150 m downwind position, sensors were similarly placed at ± 75 m, ± 50 m, ± 25 m, and 0 m. The same pattern was applied at the 250 m downwind position with crosswind offsets of ± 84 m, ± 56 m, ± 28 m, and 0 m. At each sensor location, measurements were taken at vertical heights of 1 m, 5 m, 11 m, and 17 m. Since the Phast™ model predicts plume dispersion symmetrically along the centerline, the sensor data from symmetric locations were grouped together for comparison: G01 and G07, G02 and G06, and G03 and G05 were treated as pairs, while the sensor at the centerline was considered independently. This grouping method was applied consistently across all downwind distances.

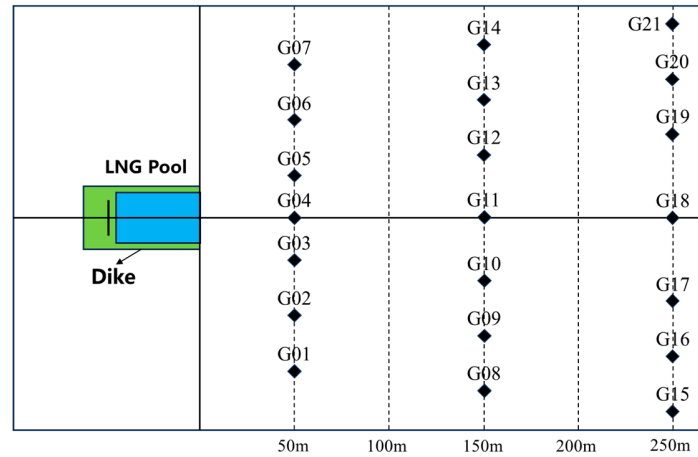


Figure 5: Falcon-1 experimental site layout map.

Fig. 6 presents a comparison between the experimentally measured concentrations and those predicted by the Phast™ at various time intervals following the LNG release. The left panel shows the comparison at a measurement height of 1 m, while the right panel corresponds to a height of 5 m. Sensor G01 was located 50 m downwind with a crosswind offset of −66 m, and sensor G07 was positioned symmetrically at +66 m.

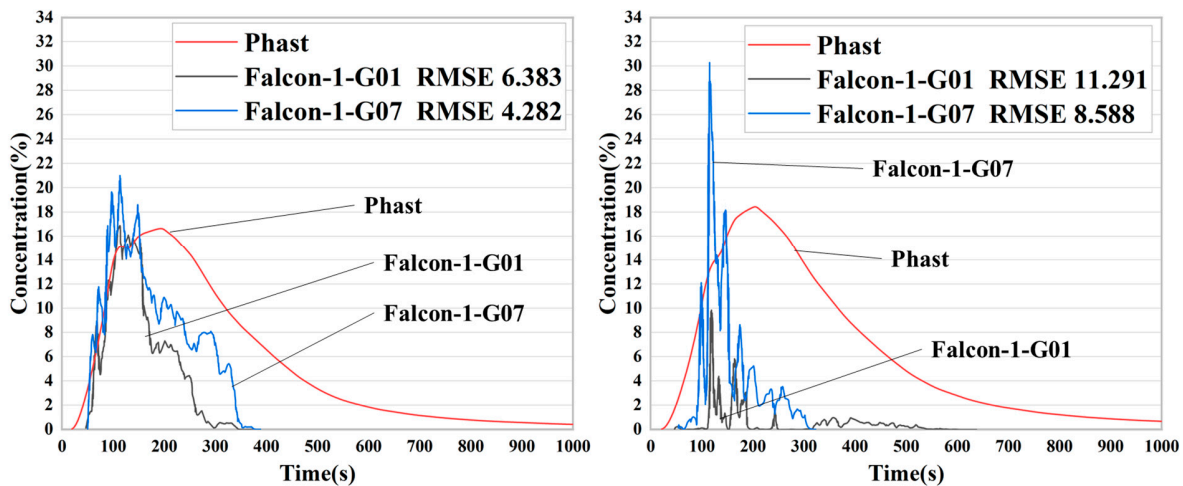


Figure 6: Comparison diagram of Falcon-1 experiments G01 and G07.

Fig. 7 compares the concentration data at two measurement heights: 1 m (left panel) and 5 m (right panel). Sensor G02 was located 50 m downwind with a crosswind offset of −44 m, while sensor G06 was

positioned at +44 m. In the Falcon-1 experiment, the concentration sensor at G02 malfunctioned, resulting in missing data for that location.

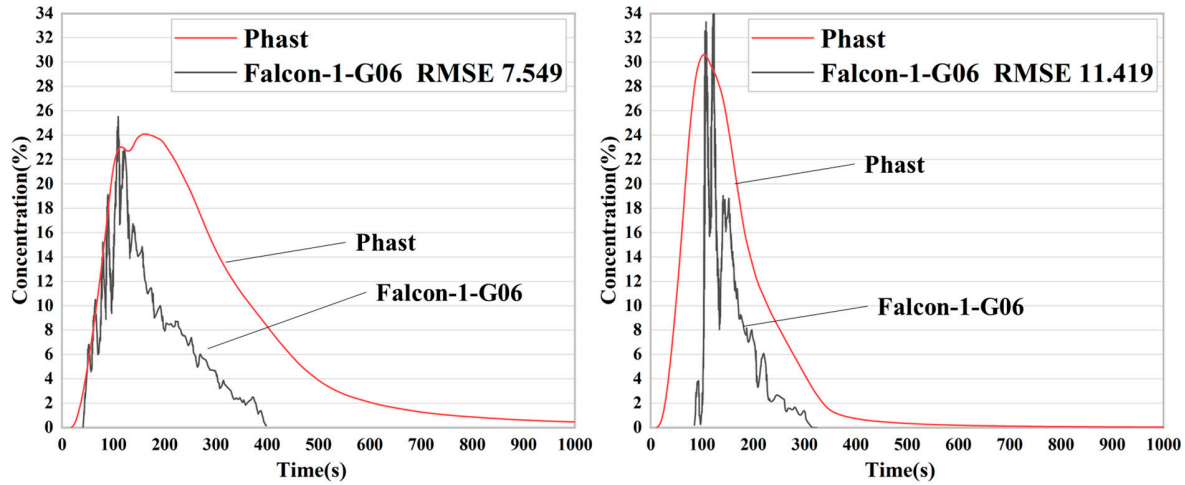


Figure 7: Comparison diagram of Falcon-1 experiments G06.

Fig. 8 presents a comparison of concentration data at two measurement heights: 1 m (left panel) and 5 m (right panel). Sensor G03 was located 50 m downwind with a crosswind offset of -22 m, while sensor G05 was positioned at $+22$ m.

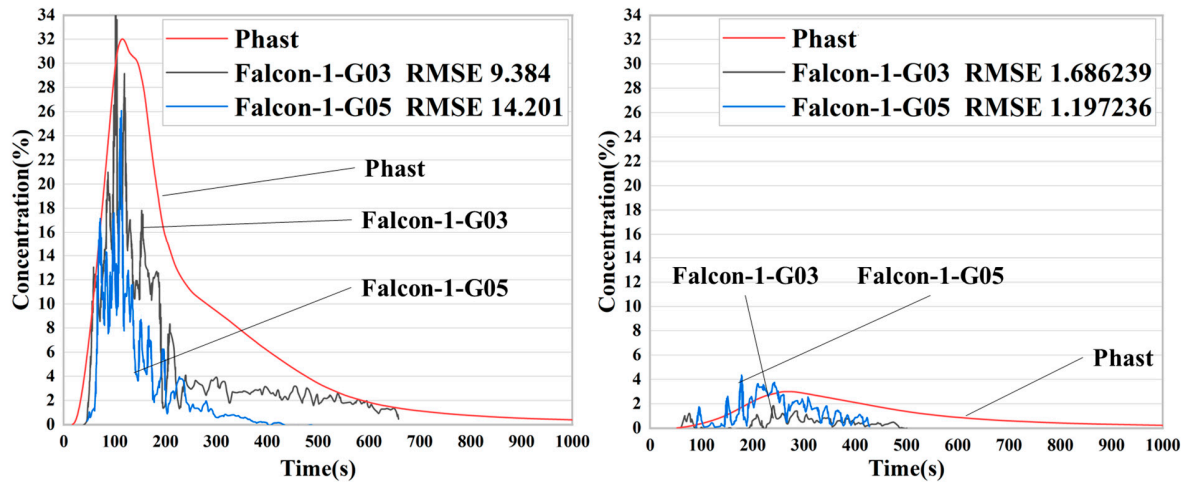


Figure 8: Comparison diagram of Falcon-1 experiments G03 and G05.

Fig. 9 compares the concentration data at measurement heights of 1 m (left panel) and 5 m (right panel). Sensor G04 was located on the centerline, 50 m downwind from the source. At this close range, Phast™ prediction shows relatively good agreement with the experimental data. However, compared to the measured values, Phast™ results exhibit a slight delay in peak concentration and a slower rate of concentration decay. The prediction accuracy at G04-5 m was notably lower.

Fig. 10 shows the concentration variations at a downwind distance of 150 m. In Fig. 10a, comparisons are presented for sensors G08–G14 at measurement heights of 1 m (left) and 5 m (right). Fig. 10b–d show comparisons at a height of 1 m between sensor pairs G09–G13, G10–G12, and the centerline sensor G11, respectively. Data for the 5-m height are missing due to sensor malfunction. Similar to the 50-m downwind

results, Phast™ predictions tend to maintain higher concentrations in the later stages compared to the experimental data and exhibit a slight delay in peak concentration.

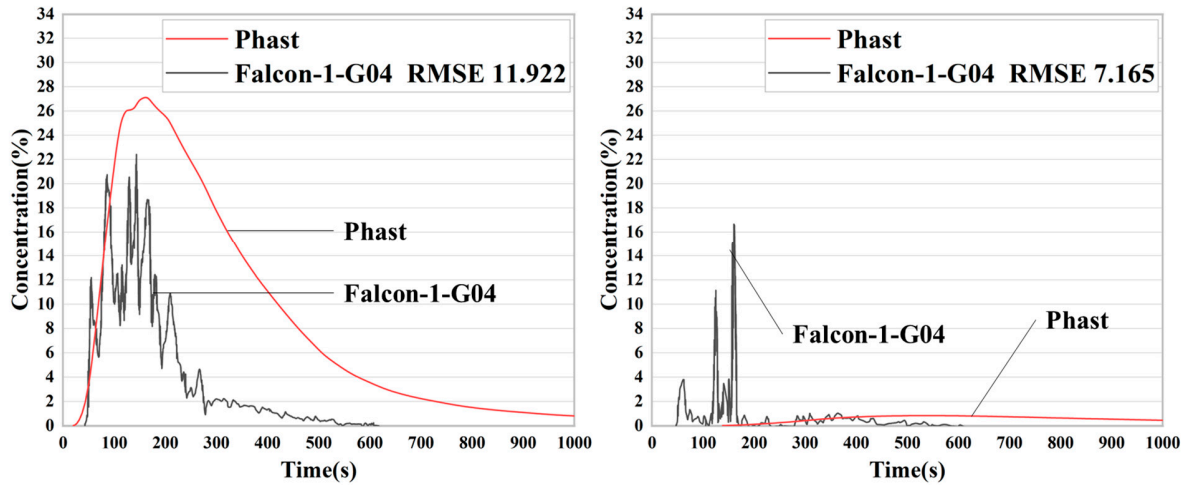


Figure 9: Comparison diagram of Falcon-1 experiments G04.

Fig. 11 illustrates the concentration variations at a downwind distance of 250 m. Fig. 11a compares sensor readings from G21–G15 at heights of 1 m (left) and 5 m (right). Fig. 11b,c present comparisons at a height of 5 m between G20–G16, and G19–G17, respectively; sensor failures resulted in missing data at 1 m for these locations. Fig. 11d shows the comparison for centerline sensor G18 at a height of 1 m, with data missing at the 5-m level due to sensor malfunction.

The results indicate that, despite some discrepancies, the Phast™ model provides a reasonably accurate reproduction of LNG vapor cloud dispersion behavior. Across sensors, at higher concentrations Phast™ tends to predict a delayed rise/peak time and a slower post-peak decay than the measurements. Conversely, in areas of lower concentration, the model predictions often occur earlier than the measured values. Across all sensor groups, Phast™ consistently underestimates the rate of concentration decay in the later stages, suggesting that the impact of the gas release is prolonged in the simulation. Notably, the model shows better agreement with experimental results at shorter downwind distances and lower measurement heights. The discrepancies between simulated and observed data may be attributed to factors such as ground heat transfer and atmospheric humidity, which are not fully captured by the model.

4 Sensitivity Analysis of LNG Dispersion

4.1 Configuration of Simulation Parameters

In this study, the natural gas mixture consists of methane (94.7% by mass), ethane (3.9%), and nitrogen (1.4%). The initial pressure and temperature inside the storage vessel are set to 4.48 bar and -160°C , respectively. The release duration is 100 s, with a release height of 2 m and a total release volume of 1000 m^3 . The bund height is 8.7 m, and the liquid pool area is 2400 m^2 . The sensitivity analysis focuses on the following parameters: orifice diameter, release angle, wind speed, atmospheric stability, surface roughness, and ambient temperature.

Orifice Diameter Settings: According to the EGIG (European Gas Pipeline Incident Data Group) gas pipeline incident database (1970–2019) [24], most oil and gas pipeline leaks are caused by corrosion-induced cracking, while large-diameter rupture events are relatively rare. Therefore, in this study, the leakage orifice diameters are set to 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm.

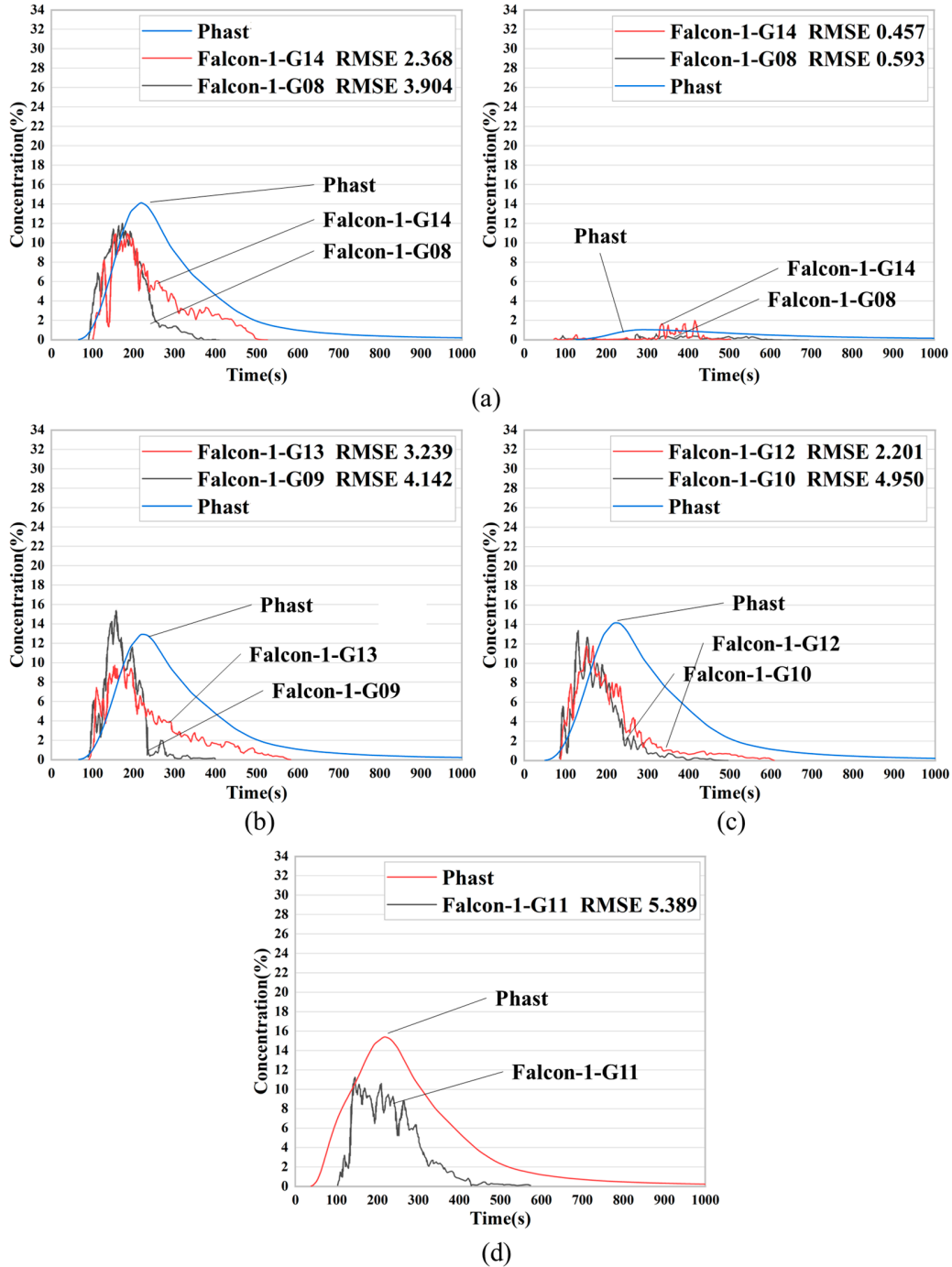


Figure 10: Comparison diagram of Falcon-1 and Phast™ predictions at 150 m downwind: (a) comparisons for sensors G08 and G14 at measurement heights of 1 m (left) and 5 m (right); (b) comparison between sensors G09 and G13 at a measurement height of 1 m; (c) comparison between sensors G10 and G12 at a measurement height of 1 m; (d) comparison at the centerline sensor G11 at a measurement height of 1 m.

Release Angle Settings: In general, LNG containers operate under high internal pressure, and leakage through an orifice often results in high-velocity discharge. This enhances the influence of the release angle on dispersion behavior, affecting factors such as vertical plume height and liquid pool formation. In this study, the release angles are set to 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°.

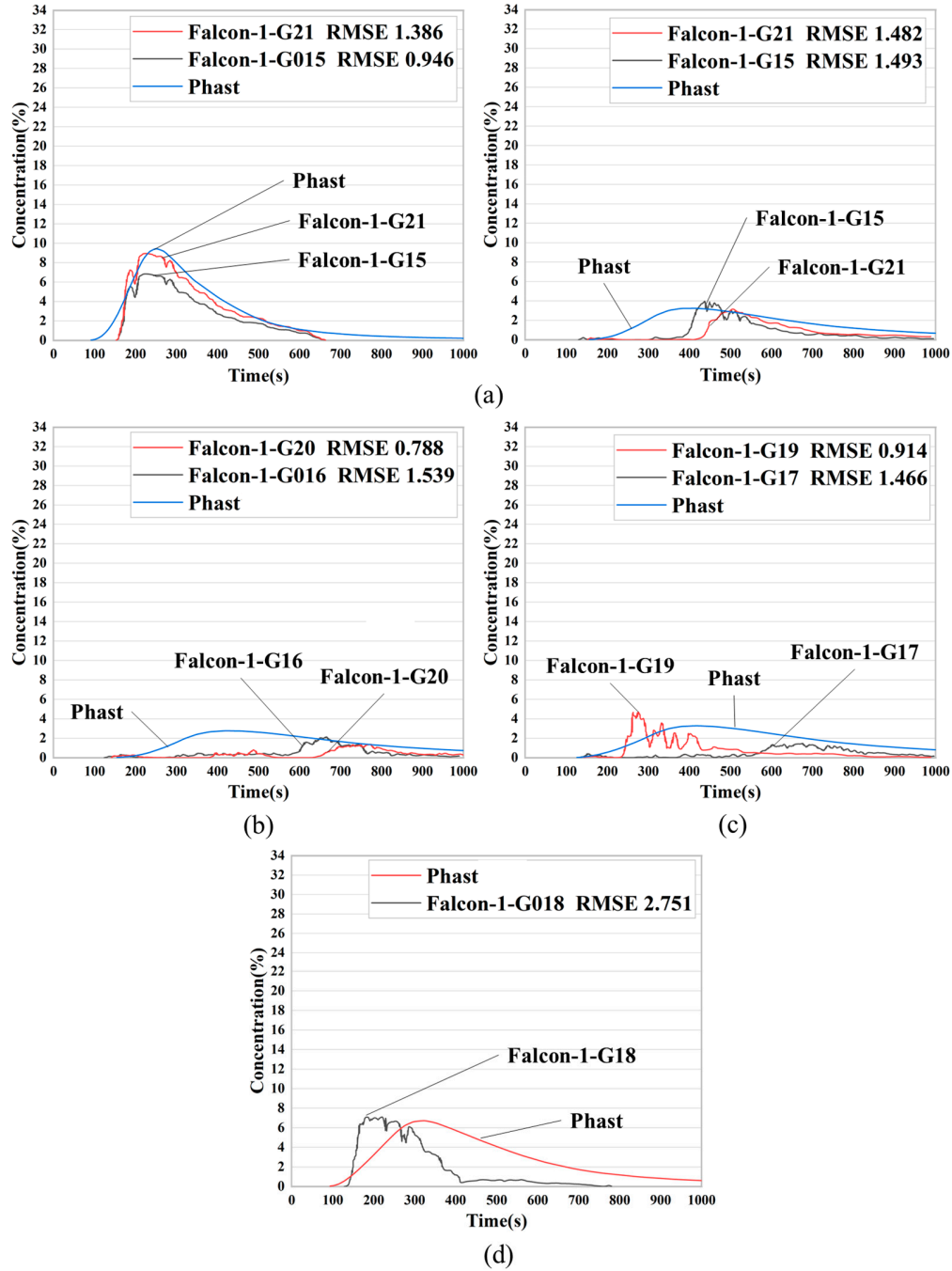


Figure 11: Comparison diagram of Falcon-1 and Phast™ predictions at 250 m downwind: (a) comparisons for sensors G15–G21 at measurement heights of 1 m (left) and 5 m (right); (b) comparison between sensors G16 and G20 at a height of 5 m; (c) comparison between sensors G17 and G19 at a height of 5 m; (d) comparison at the centerline sensor G18 at a height of 1 m.

Ambient Wind Speed and Temperature Settings: This study uses multi-year average wind speed and air temperature data from a representative meteorological station. As shown in Fig. 12, the simulations adopt wind speeds of 1.5 m/s, 1.6 m/s, 1.7 m/s, 1.9 m/s, 2.0 m/s, 2.5 m/s, 3.0 m/s, and 4.0 m/s. Ambient temperatures are set to 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C.

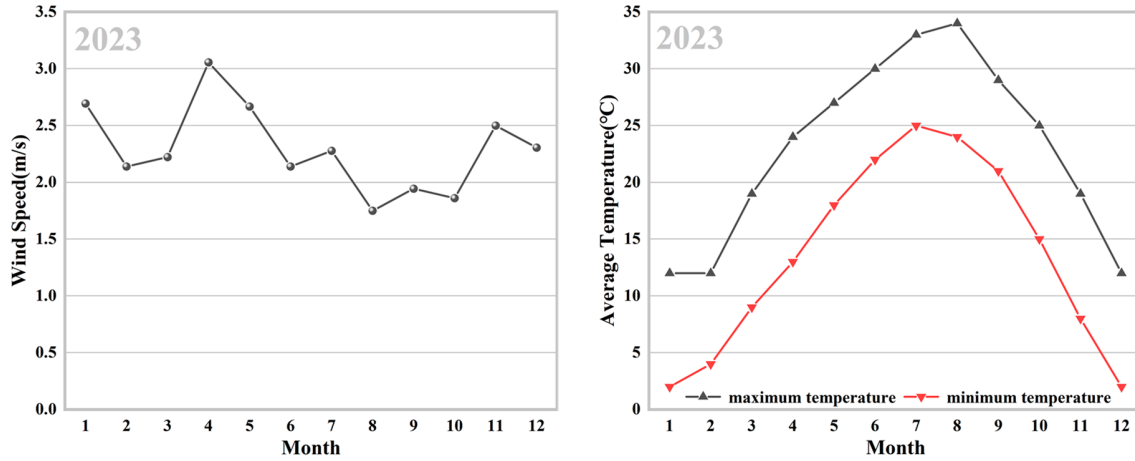


Figure 12: Annual average temperature and average wind speed.

4.2 Orifice Diameter

Orifice diameter is one of the key parameters defining the source conditions of a leak. Based on the baseline simulation settings, six different orifice sizes are analyzed: 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm [25]. The orifice diameter is a critical factor in LNG leakage behavior, as it directly influences the leakage rate. Larger orifices result in higher release rates and, consequently, wider dispersion ranges. As shown in Fig. 13, the left panel illustrates the LNG dispersion contours in the downwind direction, while the right panel presents the relationship between the maximum downwind distance and orifice size. Both the maximum dispersion distance and the affected area increase with larger orifice diameter. As expected from dense-gas theory and prior LNG/UDM studies, larger orifices yield higher release rates and longer downwind reach.

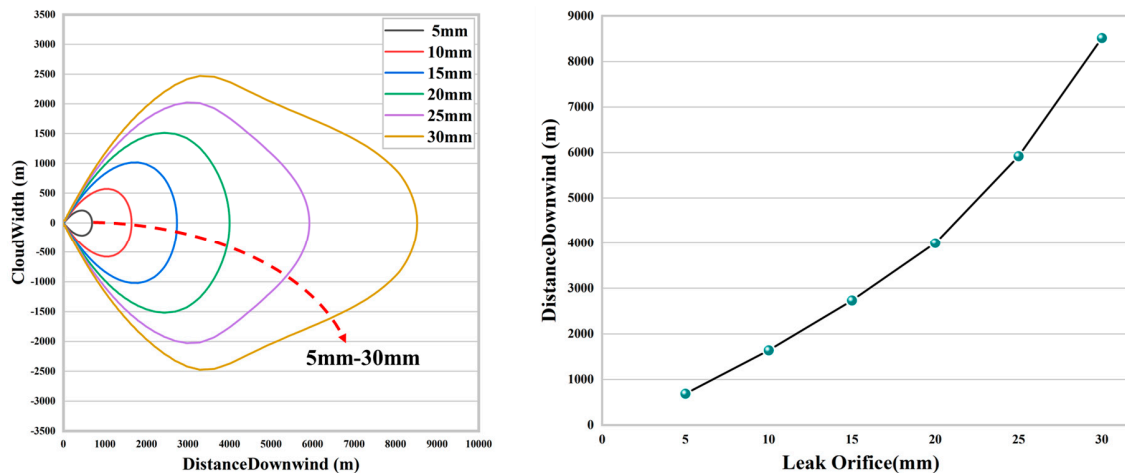


Figure 13: Dispersion top view and maximum downwind distance at different apertures.

4.3 Release Angle

With all other parameters fixed at the baseline values, the release angle (measured from the horizontal) was varied from 0° to 90° in 10° increments. Release angle is a key source-term parameter, especially for pressurized LNG systems where high discharge momentum makes the release direction important. As shown in Fig. 14, the left panel presents a side view of the downwind dispersion. Release angle significantly

affects the vertical extent of the gas cloud. At larger angles (more upward releases), transport becomes increasingly wind-dominated, so further increases in angle lead to only small changes in the maximum downwind distance. However, at smaller angles, even modest increases in the angle lead to sudden increases in the maximum downwind distance. This indicates a critical angle at which the maximum downwind distance is attained. Some assessments adopt a conservative “critical angle” near $\sim 19^\circ$ for worst-case screening, while others use 30° from horizontal as a default for above-ground releases. Fig. 14 (right) shows that at large release angle, the maximum downwind impact distance is about 1.3 times that of a horizontal release.

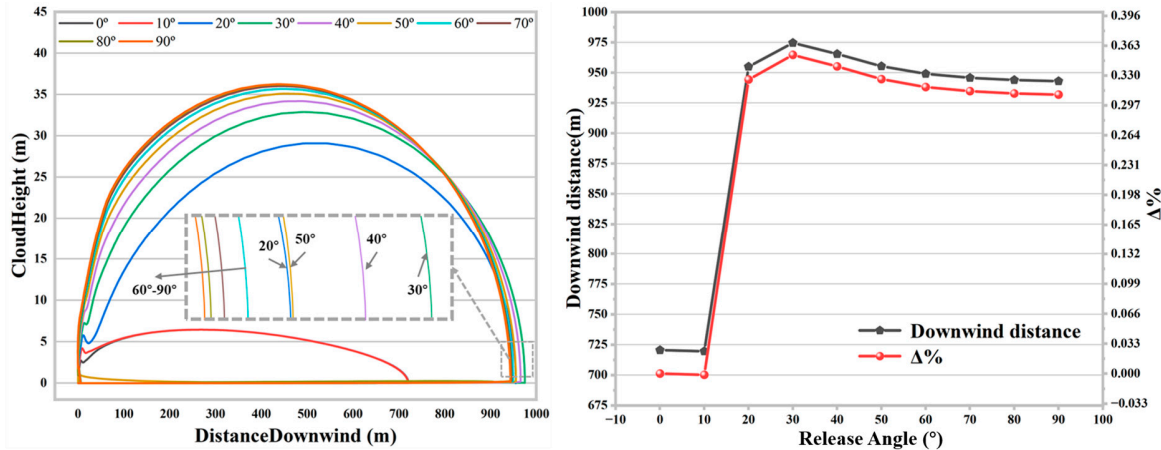


Figure 14: Side view of the release centerline at different angles and maximum downwind distance.

4.4 Ambient Wind Speed

Wind speed strongly influences vapor-cloud dispersion by controlling both advection and mixing. With all other parameters fixed at the baseline values, wind speed was varied from 1.5 to 4.0 m/s (selected values: 1.5 m/s, 1.6 m/s, 1.7 m/s, 1.9 m/s, 2.0 m/s, 2.5 m/s, 3.0 m/s, and 4.0 m/s). At lower wind speeds, increasing wind speed tends to extend the dispersion distance. However, at higher wind speeds, the enhanced turbulence can alter the dispersion pattern significantly.

As shown in Fig. 15 (left), within the low wind speed range, the downwind dispersion distance increases steadily with wind speed. At higher wind speeds, the maximum downwind dispersion distance shows a sudden decrease. Fig. 15 (right) displays a side view along the plume centerline. Compared to the top view, it is evident that under low wind speed conditions, both the horizontal dispersion distance and the vertical extent of the vapor cloud increase with wind speed. As wind speed increases, near-surface vertical shear strengthens and the production of turbulent kinetic energy rises, thereby increasing the turbulent diffusivity. The larger diffusivity accelerates entrainment and dilution, lofting the cloud and broadening it laterally. At low wind speeds, increased advection extends the downwind reach. At higher wind speeds, stronger mixing reduces the ground-level centerline distance to the threshold concentration, while plume height and crosswind spread increase. This two-regime response accords with dense-gas physics: small increases in wind speed initially carry the cloud farther, but once entrainment and dilution dominate, ground-level hazard distances shorten while plume height and cross-wind spread intensify.

4.5 Atmospheric Stability

In general, greater atmospheric stability suppresses turbulent mixing and slows dilution of the vapor cloud. In this study, a range of atmospheric stability classes was examined to evaluate their effects: A, A/B,

B, B/C, C, C/D, and D. Pasquill–Gifford stability classes were assigned using the Turner method based on 10 m wind speed and daytime insolation (or nighttime cloud cover). The intermediate labels A/B, B/C, and C/D are transition bins in the standard lookup tables, used when the meteorological inputs fall near the boundary between two adjacent classes. Fig. 16 presents both top and side views of LNG dispersion under different stability conditions. As atmospheric stability increases, the horizontal dispersion distance becomes longer, while the vertical dispersion range decreases. More unstable conditions enhance vertical mixing, but they do not necessarily increase the downwind distance to a given threshold because dilution is faster.

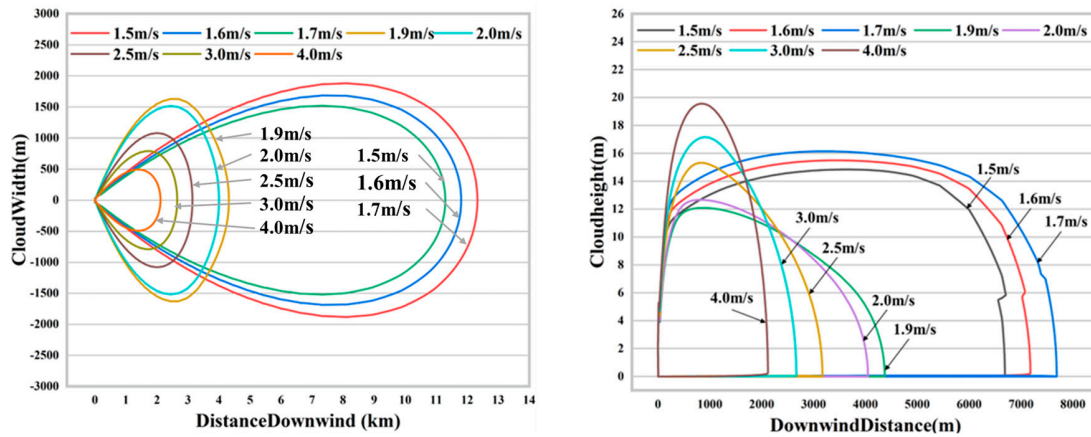


Figure 15: Top view of dispersion and side view of dispersion centerline at different environmental wind speeds.

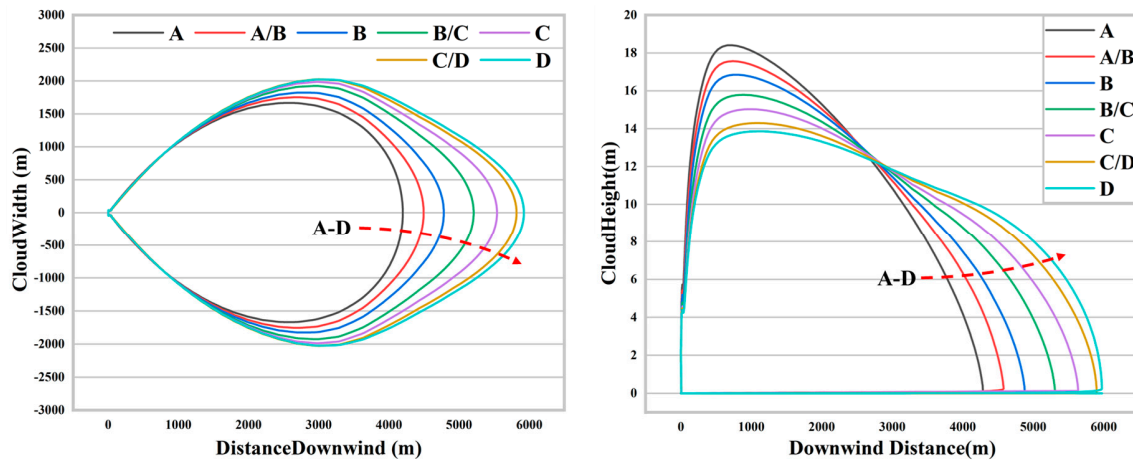


Figure 16: Top view of dispersion and side view of dispersion centerline at different atmospheric stabilities.

4.6 Roughness Levels

For the surface roughness length (z_0), representative terrain categories were considered: 0.03 m (open grassland), 0.10 m (low crops/shrubs), 0.25 m (taller crops/shrubs), 0.50 m (mixed grassland and shrubs), 1.0 m (forest/suburban), and 3.0 m (urban). Fig. 17 presents comparative views—both top and side views—for different roughness values. Surface roughness has a notable impact on the vertical dispersion of the vapor cloud and reduces the maximum downwind distance. Higher roughness increases turbulence and promotes entrainment and dilution, thereby limiting the ground-level downwind extent of the cloud.

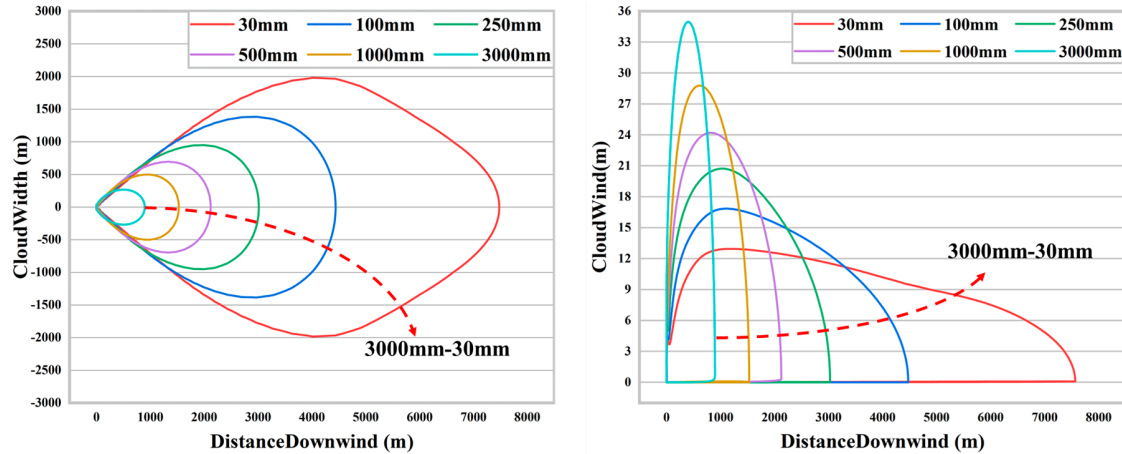


Figure 17: Top view of dispersion and side view of dispersion centerline at different ground roughness levels.

4.7 Ambient Temperature

Within the temperature range considered, ambient temperature has a secondary influence on dispersion compared with wind and stability. In this study, seven temperature levels were evaluated: 0, 5, 10, 15, 20, 25, and 30°C. Ambient temperature primarily affects the vaporization rate of LNG following a leak. In our simulations, higher temperatures mainly increase crosswind spread. Fig. 18 shows top-view dispersion contours under different temperature conditions. At lower temperatures, variations in ambient temperature have little effect on the downwind dispersion distance. However, as temperature increases, lateral dispersion becomes significantly more pronounced. Notably, at higher temperatures, there is a sharp increase in lateral dispersion compared to lower temperatures, while the downwind dispersion distance decreases substantially. Compared with primary drivers such as wind speed, atmospheric stability, surface roughness/obstacles, and source strength (orifice/flow rate), ambient temperature generally plays a secondary role in the behavior of dense-gas/LNG clouds. Under a consistent baseline in this study, we analyzed the temperature response. In warm-season/high-temperature scenarios, the far-downwind ground-level hazard distance tends to shorten while the cross-wind impact zone widens; conversely, under colder conditions, lateral spread is smaller but the downwind reach is more persistent. Accordingly, relative to prior work that was largely qualitative, our study provides quantified magnitudes and directions for the temperature effect, enabling its incorporation into site selection and emergency planning.

5 Conclusion

- (1) The size of the leakage orifice is one of the key determinants of the release rate. An increase in orifice diameter leads to a higher leakage rate, resulting in a larger initial vapor cloud and an extended dispersion range. Both the maximum downwind distance and the overall affected area increase with orifice size.
- (2) The release angle primarily influences the initial formation position of the gas cloud. There exists an optimal angle at which the dispersion distance is maximized. At smaller angles, changes in angle have a significant impact on dispersion distance, whereas near 90°, this influence diminishes and shows a decreasing trend.
- (3) Wind speed is another critical factor affecting the dispersion distance and direction of the vapor cloud. At lower wind speeds, increased wind enhances dispersion distance. However, at higher wind speeds,

intensified turbulence alters dispersion behavior—causing a sudden decrease in downwind distance, a sharp increase in lateral spread, and greater vertical dispersion.

- (4) Higher atmospheric stability reduces turbulence, making vapor clouds less likely to disperse and slowing down their spread. Under highly stable conditions, horizontal dispersion distance increases while vertical spread decreases. Conversely, lower stability promotes vertical dispersion but does not necessarily enhance downwind transport.
- (5) Surface roughness significantly affects vertical dispersion of the vapor cloud and strongly inhibits downwind transport. In particular, high surface roughness conditions effectively reduce the downwind dispersion rate.
- (6) Temperature has a relatively minor influence on vapor cloud dispersion compared to other factors. It mainly affects the vaporization rate of LNG after release. While higher temperatures expand the extent of vapor cloud dispersion—especially in the crosswind direction—low temperatures show minimal effect on downwind distance. At higher temperatures, lateral dispersion increases sharply, while downwind dispersion decreases significantly.
- (7) Safety Implications: Based on the simulation results, it is essential to maintain heightened vigilance in potentially hazardous downwind areas during LNG leakage incidents. In the event of a release, emergency personnel conducting containment operations near the source should be equipped with appropriate respiratory protection and positioned upwind whenever possible to avoid inhalation of harmful gases and the risk of asphyxiation or poisoning.

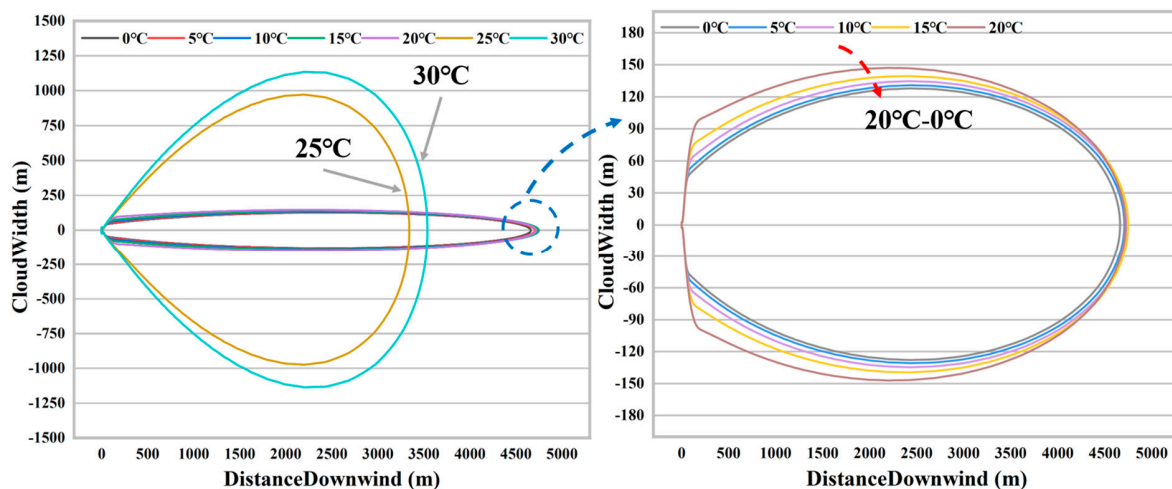


Figure 18: Top view of dispersion at different environmental temperatures.

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Conflicts of Interest: The authors declare no conflicts of interest.

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