

Article

The Influence of Ventilation Conditions on LPG Leak Dispersion in a Commercial Kitchen

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Abstract: With the extensive use of liquefied petroleum gas (LPG) in the catering industry, leakage explosions have become frequent. This study employs numerical simulations to investigate the diffusion patterns of LPG leakage under various ventilation conditions. The results show that there is a logarithmic relationship between the wind speed and the volume of a propane gas cloud under natural ventilation. In the wind speed ranges of 1.5 to 3.3 m/s and 7.9 to 10.7 m/s, a small increase in wind speed leads to a significant reduction in gas cloud volume (97.2% and 95.05%, respectively). Under forced ventilation, the volume of the gas cloud decreases by 90.6%, from 6.67 m³ at higher air exchange rates (22.1 and 24.3 times/h), reducing explosion risks. When leakage occurs at the stove, the optimal combination for dispersing the propane combustible gas cloud is window opening at position 1 and fan at position a. The volume of the gas cloud at window position 1 increases exponentially with the distance between the fan and the leak source. The fan is installed within 2.786 m from the leak source to ensure that the gas cloud volume remains below 0.5 m³. These findings provide valuable insights for the design and the optimization of ventilation systems and layouts in commercial kitchens.

Keywords: LPG leakage; confined space; natural ventilation; forced ventilation



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1. Introduction

As an efficient and clean energy, liquefied petroleum gas (LPG) has found extensive application in the catering and residential sectors, earning the title of “the omnipresent clean energy of the 21st century”. Its importance in the global energy consumption framework is rapidly increasing [1,2]. Any gas leakage incident would severely endanger human life and property security. Over the decade from 2013 to 2022, the consumption of LPG in China increased from 28.23 million tons to 68.35 million tons, with a yearly growth rate of 10.3% [3,4]. Of these, 56 million households use LPG as fuel, serving a population of 101.8 million, which falls under the scope of urban gas management. Over the past

five years, LPG leakage and explosion incidents have been frequent, with explosions resulting from LPG leaks making up approximately 60% of all gas-related accidents [5]. The occurrence of LPG leakage and explosion accidents inevitably leads to severe losses of life and substantial economic damage, potentially causing significant social repercussions [6].

During the 1970s and 1980s, a large number of full-scale, large-scale field experiments were conducted internationally, with researchers conducting extensive experiments on heavy gas leakage under various substance and leakage conditions [7]. Representative large-scale field experiments include the Burro series, Coyote series [8,9], Falcon series [10] and Thorney Island series [11]. Since the late 20th century, the application of large-scale field experiments in the heavy gas dispersion field has gradually diminished, with a shift towards smaller-scale field and laboratory experiments that are more cost-effective, manageable in terms of risk, and capable of rapidly generating repeatable data. Small-scale experiments, by obtaining repeatable data in a shorter time frame, play a crucial role in advancing the analysis of heavy gas dispersion [12]. Zheng et al. [13] established a scaling model based on similarity theory to conduct experiments, studying the effects of temperature, wind speed, and leakage rate on heavy gas leakage dispersion. Havens et al. [14] performed wind tunnel tests on CO₂, identifying the relationship between plume dispersion and vertical turbulent entrainment within the heavy gas dispersion model. Guo et al. [15] experimentally investigated the dispersion characteristics of the cloud and the formation of dry ice particles in a near-field, low-expansion CO₂ jet. Extensive research has been conducted on the gas dispersion process, leading to the development of several widely used heavy gas leakage dispersion models, such as the phenomenological model [16], box and similarity models [17], the shallow-layer model [18] and the three-dimensional fluid dynamics model [19]. Computational Fluid Dynamics (CFD) plays a significant role in the study of heavy gas dispersion. Extensive research has been conducted on external environmental factors, including wind speed [20], temperature [21], wind direction, obstacles [22], and building layout [23]. Wind speed is a key factor influencing gas dispersion. Based on an experimental platform, Shi et al. [24] developed a CFD model and concluded that the heavy gas leakage dispersion process consists of three stages: the gas concentration increase stage, the gravitational settling stage, and the passive gas diffusion stage. Poulsen et al. [25] conducted numerical simulations to investigate the impact of near-surface wind speed and wind speed fluctuations (gusts) on underground gas transport and atmospheric exchange, focusing on assessing the extent of vertical and horizontal gas transport underground. Ou et al. [26] investigated the dispersion characteristics of SF₆ gas and the optimal ventilation design for accidental leaks in industrial buildings through chamber experiments and CFD numerical simulations. Hou et al. [27] concluded that the closer the obstacle is to the leakage point, the greater the impact on hydrogen diffusion. In a mechanically ventilated space, the hydrogen concentration on the side without obstacles is 2 to 3 times that on the side with obstacles. Chen et al. [28] conducted a numerical study on the internal ventilation of a ship's engine room during construction, highlighting how equipment layout, air inlet positions, and obstruction effects impact airflow distribution and gas removal efficiency. Hao et al. [29] utilized numerical simulation methods to analyze the ventilation characteristics of courtyard buildings under wind conditions, organically integrating artificial and natural ventilation strategies to propose an optimized ventilation design scheme. Lam et al. [30] conducted simulations under a constant ambient temperature of 298 K, and found that turning off the ventilation system significantly altered the indoor recirculation pattern while enhancing the cooling efficiency of the air conditioning system.

Although the existing CFD model can solve the limitations of simplified experimental rules in practical applications, it still has some deficiencies in studying the effect of ventilation conditions on the dispersion characteristics of non-uniform LPG leaks. Therefore,

this paper constructs a three-dimensional model of a commercial kitchen based on Ansys Fluent 19.0 software to explore the effects of wind speed, fan position, and window opening position on LPG leak dispersion under natural and forced ventilation conditions. It provides an accident probability model for quantitatively assessing the impact of leaks, and offers theoretical support for the prevention, control, and emergency response of LPG leakage accidents, the optimization of ventilation system design and the reduction in explosion risk.

The remainder of this paper is organized as follows: Section 2 presents the numerical modeling framework, including the development of the physical and mathematical models, the selection of the turbulence model, boundary conditions, and mesh independence validation. Section 3 provides detailed simulation results and analyses of the dispersion characteristics of LPG under both natural and forced ventilation conditions. It examines the influence of wind speed, air exchange rate, fan–window arrangement, and their combined effect on the evolution of the combustible gas cloud. Section 4 concludes the study by summarizing key outcomes, emphasizing their significance for accident prevention and safe production in LPG-utilizing environments.

2. Numerical Simulation

2.1. Model Development

2.1.1. Physical Model

The research topic of this paper is modeling according to the actual situation of the Fuyang barbecue restaurant, with the first floor used for modeling. The model is reasonably simplified based on relevant data from an accident report, and the geometric model is shown in Figure 1.

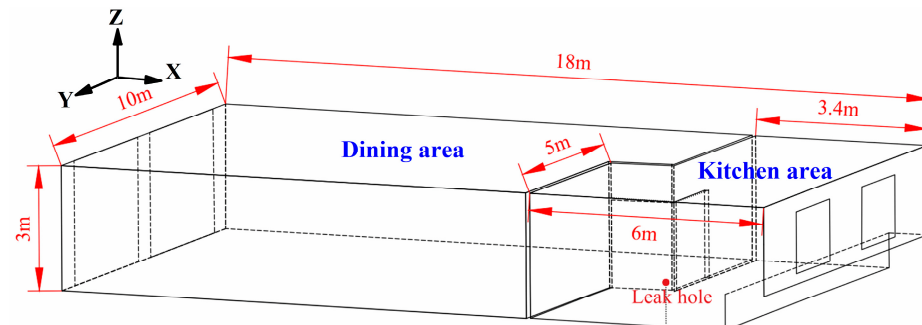


Figure 1. Physical model.

2.1.2. Mathematical Model

In this study, ANSYS Fluent software was used to simulate the leakage and explosion of liquefied petroleum gas in the kitchen of a barbecue restaurant. Considering that the actual leakage process of LPG in the barbecue restaurant is affected by many factors and the process is complex and uncertain, the following basic assumptions are made to ensure that the flow field of the established model is consistent with the actual flow field: (1) The gas leaking from the cylinder is assumed to be pure propane. (2) Propane and air are assumed to be ideal gases. (3) The mass leakage rate of propane is assumed to remain constant during the leakage process. (4) The chemical reactions between the leaking gas and air during the diffusion process are not considered. (5) The wind speed is assumed to be constant under ventilation conditions.

Based on the above assumptions, the governing equations for the LPG leakage, diffusion, and explosion problem in the kitchen include the continuity equation, momentum equation, energy equation, and species transport equation, all of which can be found in

the ANSYS User's Manual [31]. The Realizable k- ϵ turbulence model was selected for the leakage and dispersion simulations due to its improved performance in modeling buoyancy-driven indoor flows and capturing stratification effects of heavy gases. Compared with the standard and RNG k- ϵ models, it demonstrates better adaptability to complex flow conditions in confined environments such as kitchens, in which the expressions for turbulent kinetic energy and turbulent dissipation rate are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(u_i + \frac{u_i}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_K + G_b - \rho \epsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(u_i + \frac{u_i}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_K + C_{3\epsilon} G_b) + G_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (2)$$

Here, G_k is the turbulence kinetic energy produced by the mean velocity gradient; G_b is the turbulence kinetic energy produced by buoyancy; Y_M is the contribution of the fluctuation expansion in compressible turbulence to the total dissipation rate; the constants are $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.44$, $\sigma_k = 1.0$ and $\sigma_\epsilon = 1.3$.

2.2. Model Verification

2.2.1. Mathematical Model Verification

This section presents a comparison of the experimental data and simulation results from reference [32]. The experimental setup is a rectangular box with dimensions of 3 m $\times$ 1.6 m $\times$ 2.5 m. The leakage point is situated on the right side of the central plane of the apparatus, with a height of 0.9 m, a diameter of 10 mm, and a leakage flow rate of 40 L/h. The background wind speed is 0 m/s, and the gas is released in the horizontal direction. The data acquisition system is equipped with 5 CO₂ concentration sensors to continuously monitor CO₂ levels. The simulated gas concentrations at monitoring points 1, 3, and 5 were compared with the experimental results. As shown in Figure 2, the concentration curves of both datasets align closely, and the deviation between the numerical simulation and the experimental results is less than 5%.

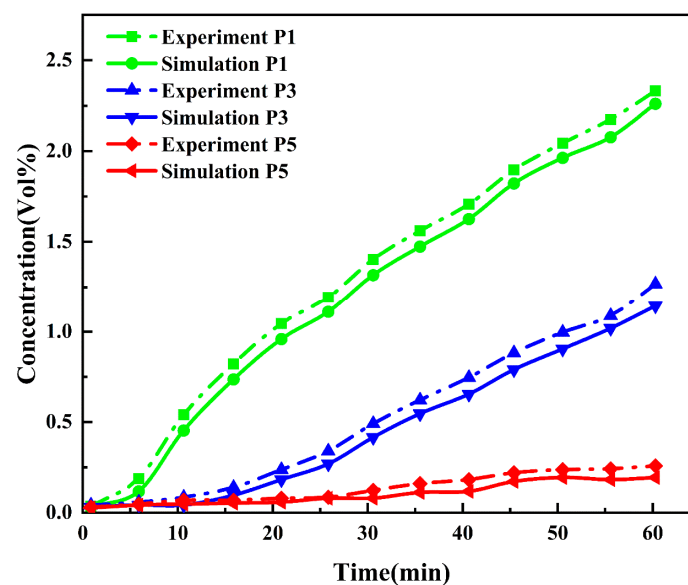


Figure 2. Numerical model verification.

2.2.2. Grid Independence Verification

The calculation domain is divided into structured grids by using the ANSYS grid method. At the leakage point, the O-mesh method is used for local refinement to obtain a

finer mesh. The final meshing result is shown in Figure 3a. This study performs a mesh independence validation for the restaurant kitchen model. A total of 5 sets of grid size gradients are defined, with grid numbers of 804,094, 954,943, 1,090,132, 1,281,170, and 1,466,607, respectively. The propane concentration's (vol%) evolution at a height of 0.3 m near the leak point inside the kitchen is shown in Figure 3b. The specific grid parameters are shown in Table 1. When the grid sizes are 1,281,170 and 1,466,607, the concentration curves nearly overlap. Therefore, considering both computational efficiency and accuracy, the grid size of 1,281,170 is chosen for simulation.

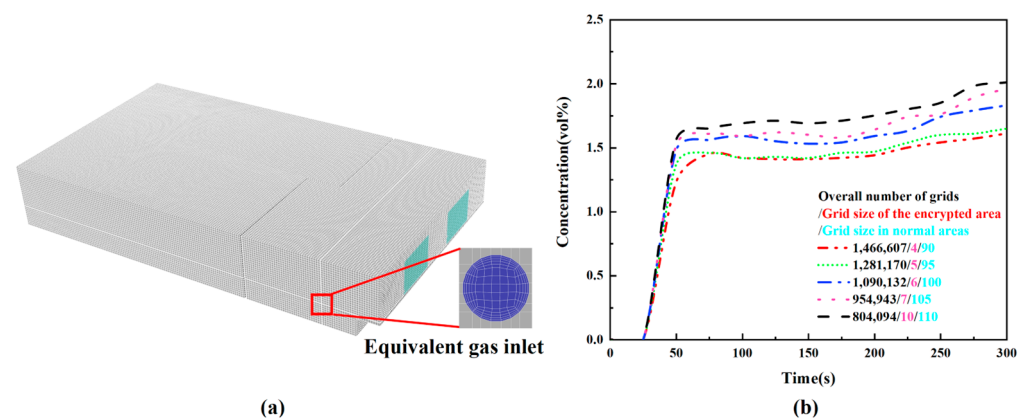


Figure 3. Grid sensitivity investigations: (a) grid division diagram; (b) grid sensitivity investigations.

Table 1. Grid size under different grid numbers.

Number of Grids	Grid Size of Encrypted Area (mm)	Grid Size in Normal Areas (mm)
804,094	10	110
954,943	7	105
1,090,132	6	100
1,281,170	5	95
1,466,607	4	90

2.3. Numerical Method

2.3.1. Boundary Conditions

The environmental pressure and temperature are set to standard atmospheric pressure (101.325 kPa) and 293 K, respectively. Taking the influence of gravity into account, the gravitational acceleration is set to 9.8 m/s^2 , directed vertically downward. According to China's national standard GB35844-2018 [33] "Regulator for Bottled Liquefied Petroleum Gas", the commercial LPG supply pressure is 5000 Pa. The boundary types and parameters used in this study are shown in Table 2.

Table 2. Boundary condition settings.

Boundary	Boundary Type	Parameter Settings
Leak Hole	Mass flow–inlet	Mass flow rate, 0.0962 kg/s; initial gauge pressure, 5000 Pa; Substance, pure propane
Window	Velocity–inlet / Pressure–outlet	initial gauge pressure, 0 Pa; substance, air
Door	Wall	Default wall roughness settings
Wall	Wall	Default wall roughness settings
Exhaust fan	Wall/Exhaust fan	Piecewise–linear

2.3.2. Computational Parameters

The leak hole in the commercial kitchen is set as the computational domain inlet, with a leak hole size of 10 mm and a leak flow rate of 0.009225 kg/s. The kitchen dimensions are 18 m × 10 m × 3 m. The specific leak dispersion case settings are shown in Table 3.

Table 3. LPG leakage dispersion case setup.

Mass Flow Rate (kg/s)	Leak Hole Size (mm)	Room Dimensions (m)	Natural Ventilation Wind Speed (m/s)	Forced Ventilation Air Exchange Rate (times/h)
0.009225	10	18 × 10 × 3	0, 1.5, 3.3, 5.4, 7.9, 10.7	5.98, 7.86, 10.6, 12.5, 16.4, 19.6, 22.1, 24.3

3. Results and Discussion

3.1. The Impact of Natural Ventilation on LPG Leakage Dispersion Patterns

When the kitchen window is open, the indoor and outdoor spaces are connected, and the wind speed will influence the dispersion process of LPG leakage in the room. In this study, the external wind speeds are set as levels 0–5, with wind speeds of 0 m/s (no wind), 1.5 m/s (level 1 wind), 3.3 m/s (level 2 wind), 5.4 m/s (level 3 wind), 7.9 m/s (level 4 wind), and 10.7 m/s (level 5 wind). It is recommended to close the window when the wind force reaches level 6 or above. Based on the “Urban Residential Area Planning and Design Standards” (GB50180) [34], a model diagram, as shown in Figure 4, is designed. The wind speed UDF is imported, and after running for 300 s, a stable wind field is obtained. After 300 s, the leak hole is opened, and the indoor stable wind field after 300 s is shown in Figure 5.

Figure 6 shows the variation in the distribution of the propane combustible gas cloud (regions where the propane volume fraction $\geq 2.1\%$) under different natural wind speeds. Figure 7 presents the time-series curve of the variation in the volume of the propane combustible gas cloud, and Figure 8 illustrates the time-series curve of propane concentration changes at the alarm monitoring point in the commercial kitchen.

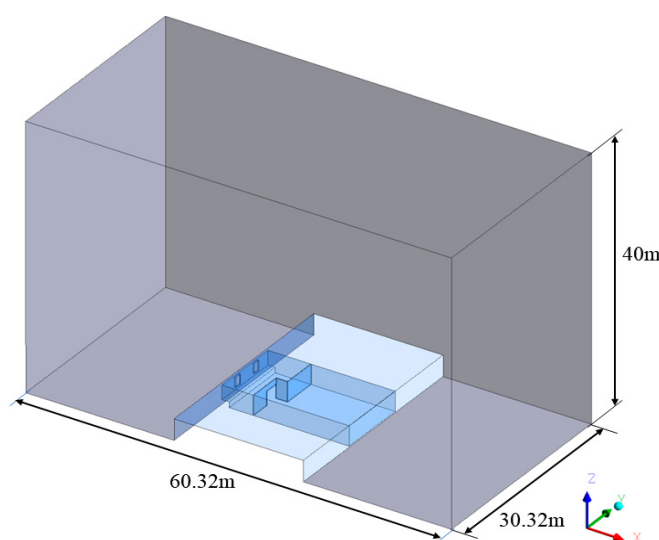


Figure 4. Physical model diagram.

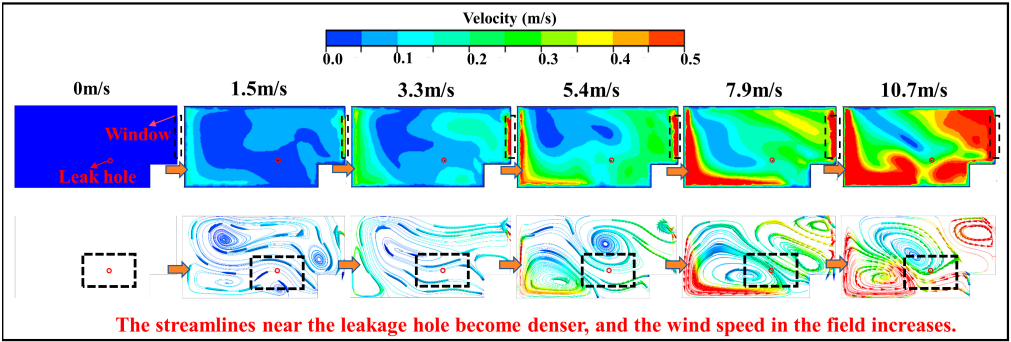


Figure 5. Indoor wind field and streamline diagram after 300 s.

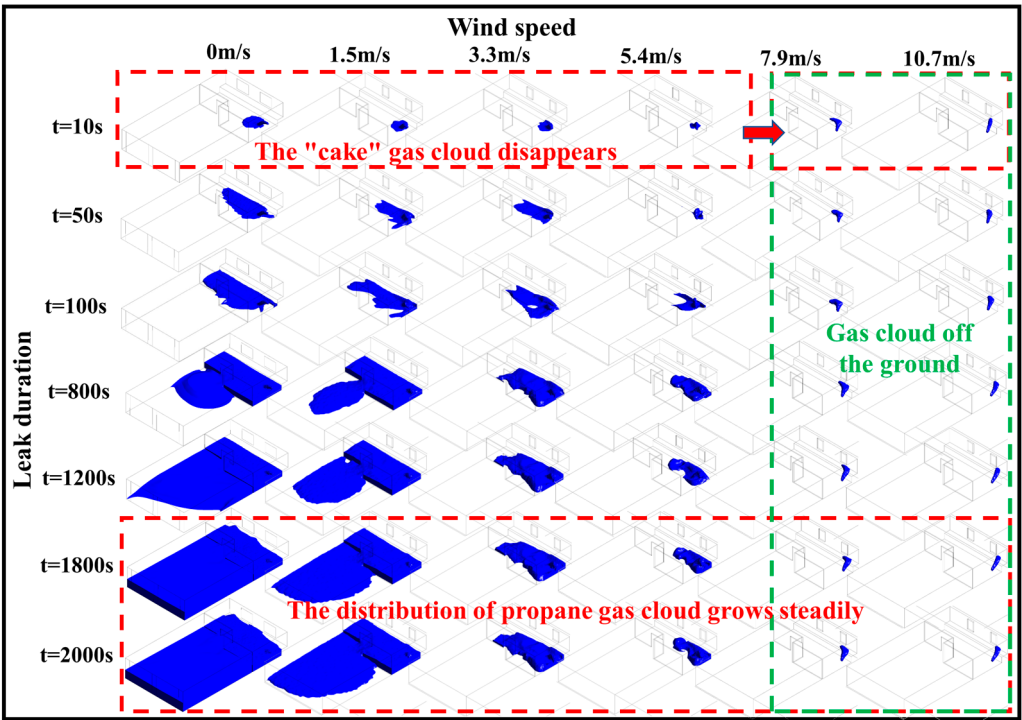


Figure 6. Distribution of propane combustible gas clouds at various wind speeds.

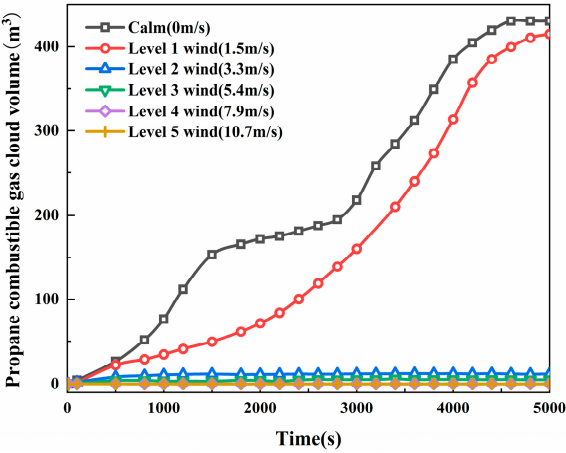


Figure 7. Curve of propane combustible gas cloud volume variation with time.

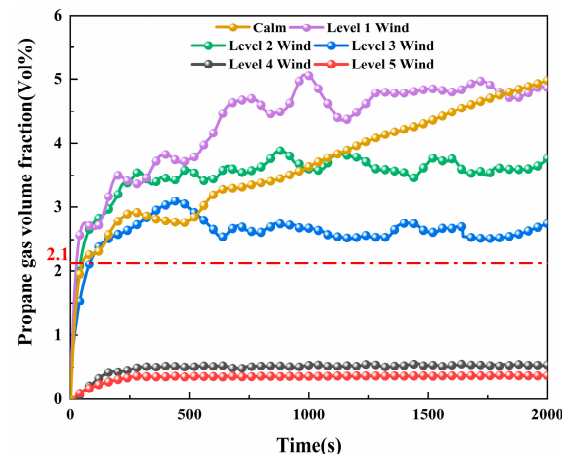


Figure 8. Time-dependent variation of concentration at the alarm monitoring point.

Overall, with the increase in wind speed, the expansion rate of the propane combustible gas cloud is suppressed, and its volume decreases. Propane gas is denser than air and typically spreads along the ground. As shown in Figure 7, 10 s after the leak, the “disk-shaped” gas cloud accumulated on the kitchen floor decreases as the wind speed increases. When the wind speed was more than 7.9 m/s, the propane gas cloud detached from the ground and assumed an upward “tadpole-shaped” form in the vertical direction of the leak hole. After 1200 s of propane leakage, the gas cloud distribution slowly expanded and eventually stabilized under all wind speed conditions. Figure 8 shows that after 5000 s of propane leakage, the volume of the propane combustible gas cloud stabilized under all wind speed conditions, reaching values of 430.1 m³ (the maximum volume in the kitchen), 414.92 m³, 11.73 m³, 5.13 m³, 0.254 m³, and 0.0912 m³. Figure 9 shows that when the wind speed was more than 7.9 m/s, the propane concentration at the indoor alarm monitoring points remained below the lower explosive limit concentration of 2.1%. It can be observed from Figure 5 that at low wind speeds, the streamlines near the leak hole were sparse, and the flow velocity was low. The gas primarily diffused horizontally and vertically along the concentration gradient. As the wind speed increased, the streamlines near the leak hole became denser, the flow velocity increased, the turbulence intensified, the mixing rate of propane and air was accelerated, and the distribution range and volume of the propane combustible gas cloud were significantly reduced. When the wind speed was more than 7.9 m/s, the upward wind near the leak hole became stronger than the gravitational settling effect of propane, causing the propane combustible gas cloud to lift near the leak hole. Thus, in the emergency response to and prevention of propane leakage, enhanced ventilation can effectively slow the accumulation of leaking gas and reduce the risk of fire and explosion.

Figure 9 illustrates the relationship between wind speed and the volume of the propane combustible gas cloud after stabilization. With the increasing wind speed, the volume of the propane combustible gas cloud generally decreases. A fitting of wind speed and propane combustible gas cloud volume yields an R value of 0.9999 and a residual square of 0.0001. The relationship between wind speed and propane combustible gas cloud volume is logarithmic, as indicated by Equation (3),

$$y = 1.76 + 428.44 / (1 + (x/2.172)^{8.92}) \quad (3)$$

The impact of wind speed changes on the volume of the propane combustible gas cloud is non-linear. In the intervals from level 1 to level 2 and from level 4 to level 5 wind (with volume reductions of 97.2% and 95.05%, respectively), a small increase in wind speed

can significantly reduce the volume of combustible gas cloud and effectively reduce the explosion risk of the propane gas cloud.

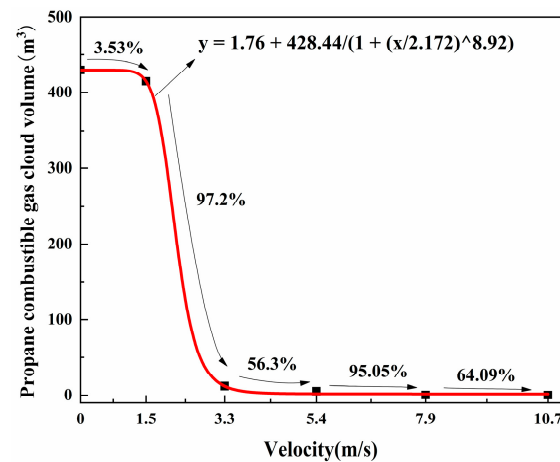


Figure 9. The relationship between wind speed and propane combustible gas cloud volume.

3.2. The Impact of Forced Ventilation on LPG Leakage Dispersion Patterns

3.2.1. Operating Conditions Setup

Based on the “Building Design Fire Protection Code” (GB 50016) [35], considering factors such as air flow, pressure requirements, and explosion-proof performance, the BT35 explosion-proof axial fan (hereinafter referred to as the fan) is chosen as the forced ventilation fan to study its impact on LPG leakage dispersion patterns. According to the “Commercial Kitchen Design Code” (TSRCA000003) [36], the distance from the lower edge of the fan to the floor is 0.3 m, and the window opening size is designed as 1 m × 1.5 m based on the air replenishment requirements. The fan model and parameters are provided in Table 4.

Table 4. Fan parameters.

Fan Model	BT35-11-5				BT35-11-5.6			
Air volume (m ³ /h)	3142	4129	5566	6595	8667	10,379	11,682	12,812
Static pressure (Pa)	53	59	65	151	169	174	186	232
Wind speed (m/s)	4.45	5.86	7.88	7.44	9.78	11.7	13.18	14.45
Air exchange rate (times/h)	5.98	7.86	10.6	12.5	16.4	19.6	22.1	24.3

Figure 10 illustrates the time-series curve of propane volume concentration variation. After 136 s of propane leakage and dispersion, the propane concentration at the combustible gas detector in the kitchen reaches the lower explosive limit concentration (2.1%), at which point the volume of the propane combustible gas cloud in the kitchen reaches 6.67 m³. The fan is then activated to quickly expel the propane combustible gas cloud from the kitchen.

In order to analyze the impact of window opening position and fan position on the distribution of propane combustible gas clouds, three window opening positions (1, 2, 3) and four fans (a, b, c, d) are set. The coordinate positions are (10 m, 0.58 m, 1.5 m), (10 m, 0.58 m, 3.5 m), (0 m, 0.58 m, 2.7 m) and (0 m, 0.58 m, 2.7 m), respectively. The settings of two leakage positions—stove (8.5 m, 0.85 m, 0.5 m) and gas cylinder regulator (10 m, 1 m, 2 m)—are shown in Figure 11.

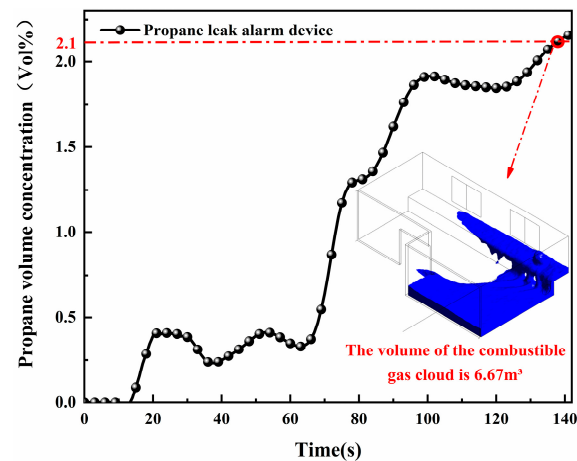


Figure 10. Time-series curve of propane volume concentration variation.

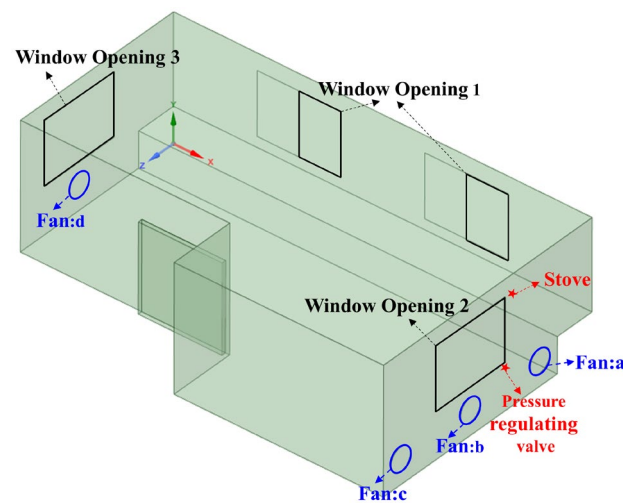


Figure 11. Schematic diagram of fan and window opening positions.

3.2.2. The Impact of Air Exchange Rate on Propane Leakage

Figure 12 presents the streamline turbulence kinetic energy diagram at a height of $Y = 1$ m under varying ventilation rates. Figure 13 illustrates the dynamic evolution of the propane combustible gas cloud distribution caused by leakage when the leak hole is at the stove, the window opening is at position 1, and the fan is at position b under varying ventilation rates.

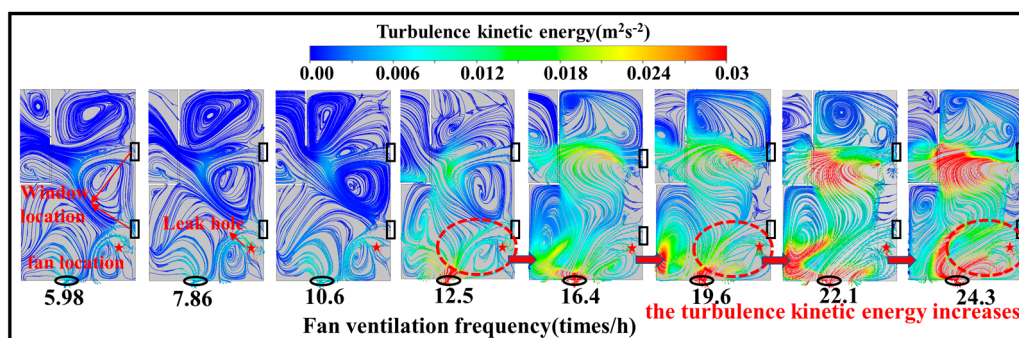


Figure 12. Streamline turbulence kinetic energy diagram at $Y = 1$ m height under different ventilation rates.

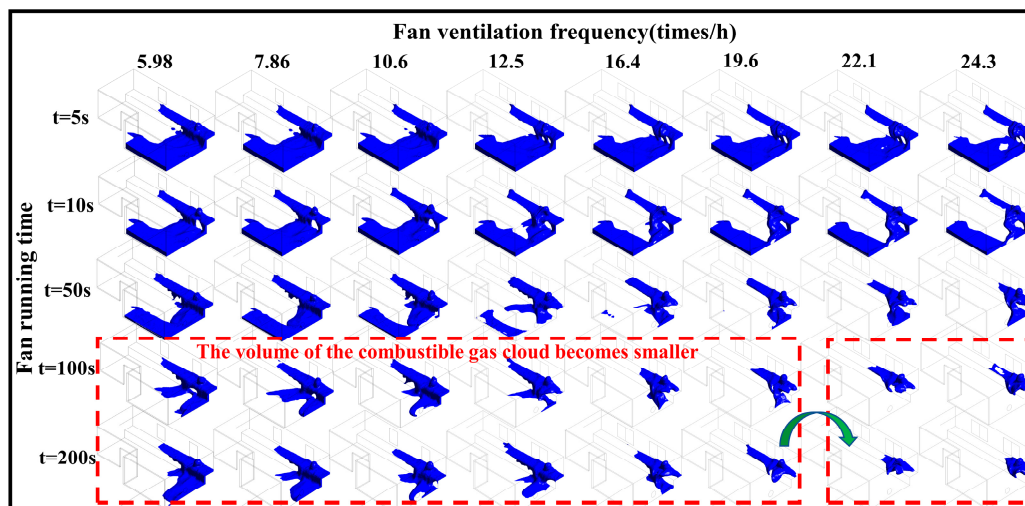


Figure 13. Evolution of propane combustible gas cloud distribution under different ventilation rates.

As ventilation time increases, the distribution range and volume of the combustible gas cloud gradually decrease, and the number of air exchanges plays a decisive role in the dispersion speed and distribution pattern of the propane gas cloud. According to Figures 12 and 13, during the first 50 s of fan operation, the distribution range of the propane combustible gas cloud decreases with the increase in fan air exchange rates. When the air exchange rate is lower (5.98 to 10.6 times/h), the turbulence kinetic energy near the leak hole is weak, the airflow speed is low, and the dispersion effect on the propane gas is insufficient, which results in a large combustible gas cloud area on the kitchen floor, thereby increasing the risk of explosion. At higher air exchange rates (22.1 times/h and 24.3 times/h), the turbulence kinetic energy near the leak hole is larger, the airflow speed increases, and the gas disperses to a wider area. After 50 s of fan operation, under lower air exchange rates, the airflow will concentrate near the leak hole, with weaker turbulence disturbance on the side away from the fan, and the streamline distribution will become more orderly. However, at higher air exchange rates (22.1 times/h and 24.3 times/h), the turbulence kinetic energy generated by the fan is the strongest, and the gas cloud distribution range in the whole kitchen is the smallest.

Figure 14 illustrates the time-series curve of the propane combustible gas cloud volume change under different ventilation rates when the fan is at position b. Figure 15 depicts the volume of the propane combustible gas cloud after 200 s of fan exhaust.

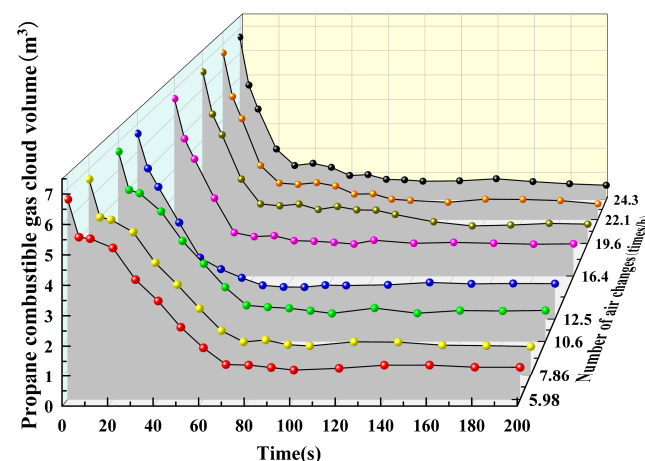


Figure 14. Volume change of propane combustible gas cloud.

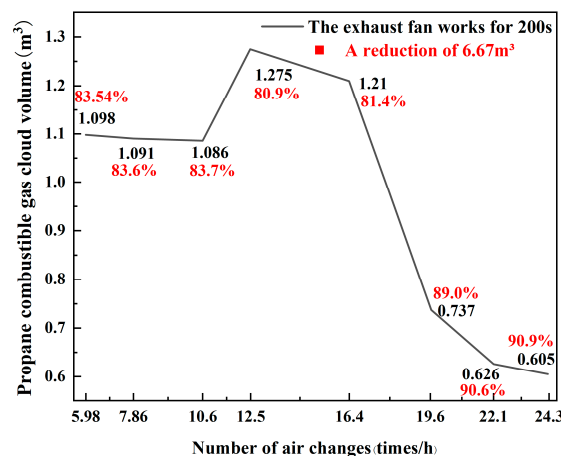


Figure 15. Volume of propane combustible gas cloud after 200s of fan operation.

As shown in Figure 14, with the increase in fan operation time, the volume of the propane combustible gas cloud decreases to a stable value. According to national standards, the required ventilation exchange rate for accidents should be at least 12 times/h [34]. As shown in Figure 15, after 200 s of fan operation, the air exchange rate increases from 22.1 exchanges per hour to 24.3 exchanges per hour. The volume of the combustible gas cloud decreases from 6.67 m³ to 0.626 m³ and 0.605 m³, with reductions of 90.6% and 90.9%, respectively, exhibiting a minimal difference. This suggests that once the air exchange rate reaches 22.1 times/h, further increases in the exchange rate will no longer effectively reduce the volume of the combustible gas cloud. Considering all aspects, it is advised to choose a ventilation rate of 22.1 times/h for commercial kitchens of similar size.

3.2.3. The Impact of Fan and Window Positions on Propane Leakage

Figure 16 illustrates the change in the distribution of the propane combustible gas cloud with different fan positions when the leak hole is at the stove and the window opening is at position 1. Figure 17 shows the streamline diagram for different window openings and for fan positions when the window opening is at position 1.

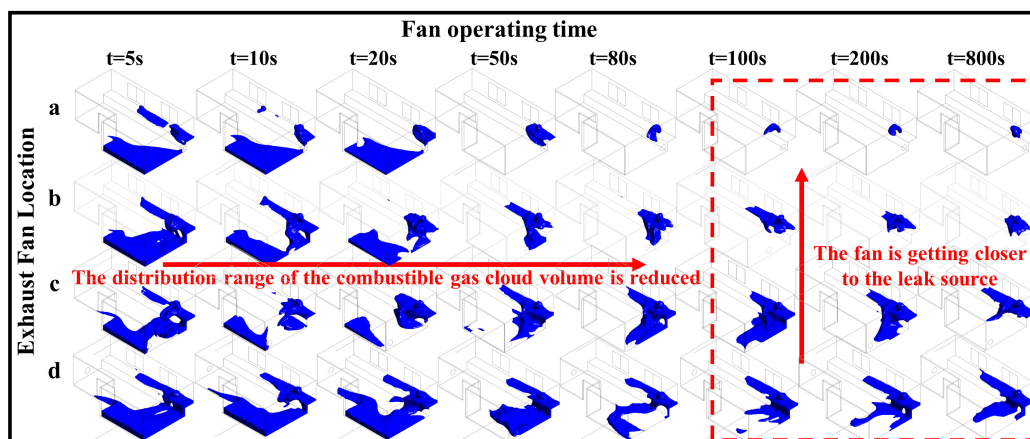


Figure 16. Evolution of propane combustible gas cloud distribution under different fan positions when the window opening is at position 1. (Exhaust fan location: a, b, c, d).

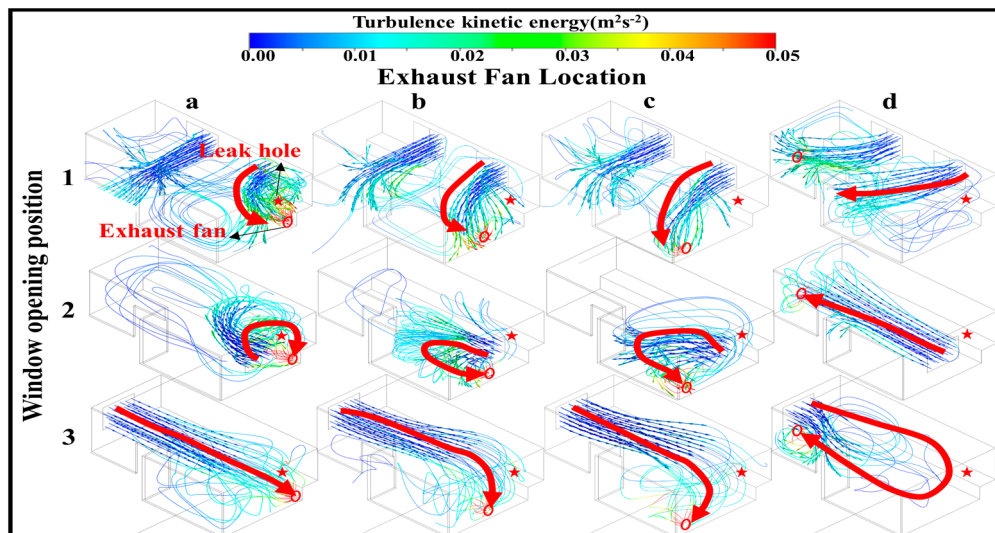


Figure 17. Flow diagrams at different window openings and fan positions when the stove leaks. (Exhaust fan location: a, b, c, d; Window opening position: 1, 2, 3).

From Figures 16 and 17, it can be concluded that, overall, as the fan operating time increases, the distribution range of the combustible gas cloud rapidly decreases and stabilizes. The closer the fan is to the leak source, the more effective the dispersion of the propane combustible gas cloud. After 80 s of operation, the fan at position a, being the closest to the leak source, forms a short and efficient exhaust airflow path between the fan and the window opening, leading to the strongest turbulence kinetic energy disturbance and the highest efficiency in dispersing the combustible gas cloud. The dispersion effect of the fan at position b is second only to that of position a. When the fan is at positions c and d, due to the distance from the leak source, the airflow path is longer, and the turbulence kinetic energy and dilution efficiency decrease significantly, making it inefficient to expel the combustible gas cloud within a short time. Therefore, when the window opening is at position 1, placing the fan at position a is the optimal approach, which can significantly reduce the distribution range of the propane combustible gas cloud and quickly control its dispersion.

Figure 18 illustrates the time-series curve of propane combustible gas cloud volume change at different window opening and fan positions. Overall, with the passage of time, the volume of the propane combustible gas cloud decreases. When the window opening is at positions 2 and 3, the dispersion effect of the fan at position d is poor, and a brief increase in the volume of the propane combustible gas cloud is observed during the overall decrease.

Based on Figures 17 and 18, it can be seen that, under all window opening positions, when the window opening is at position 1, the effective airflow path for dispersing the propane combustible gas cloud is the shortest. The fan positioned at a, which is closest to the leak source, generates the highest turbulence kinetic energy, leading to the most effective dispersion of the propane combustible gas cloud. When the fan is at position d, due to the increased distance from the leak source, the airflow path is the longest, resulting in the weakest turbulence disturbance on the propane gas cloud. As shown in Figure 18b, when the window opening is at position 2, the fan at position d is opposite the window, and the exhaust airflow path is longer, causing a delay in the airflow reaching the concentrated propane gas cloud area. Initially, the volume of the combustible gas cloud increases until the airflow in the kitchen stabilizes, and the dispersion process becomes effective. As shown in Figure 18c, when the window opening is at position 3, the fan at position d is on the same side as the window opening, far from the leak source. The short-circuit

airflow path allows fresh air to enter through the window and be directly expelled by the fan, with minimal turbulence disturbance, resulting in least effective dispersion. From Figure 18d, after 800 s of fan operation, when the window opening is at position 1 and the fan is at position a, the volume of the propane combustible gas cloud is the smallest (0.152 m³). This combination is most effective in diluting and expelling the propane gas cloud, thus reducing the explosion risk. Therefore, in comparable environments, positioning the window at opening 1 and placing the fan at location a constitutes the optimal configuration for dispersing the propane combustable gas cloud. This arrangement allows the airflow to more effectively cover the gas cloud region, thereby accelerating the dilution and dispersion of the propane cloud through turbulence.

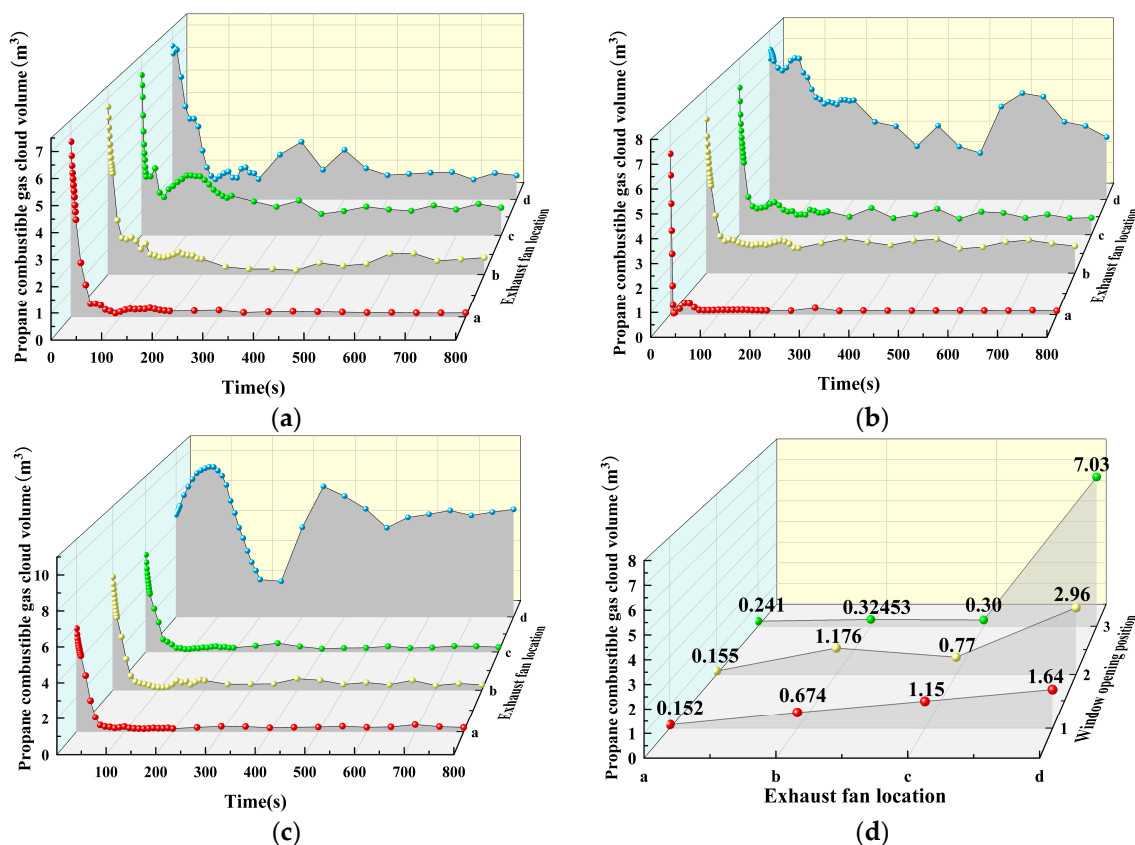


Figure 18. Time-series curves of propane combustible gas cloud volume change under different window opening positions and fan locations. These should be listed as: (a) window opening 1; (b) window opening 2; (c) window opening 3; (d) combustable gas cloud volume after 800 s of fan operation.

Since the dispersion effect of the fan is most significant when the window opening is at position 1, the volume of the combustable gas cloud in this scenario shows an exponential increase with the distance between the fan and the leak source. The specific relationship is as follows:

$$V = -0.726 + 2.844 \times (1 - \exp(-d/4.94)) \quad (4)$$

Here, d is the distance between the fan and the leak hole, in meters; V is the volume of the propane combustable gas cloud, in cubic meters. By fitting the data, to ensure the volume of the combustable gas cloud does not exceed 0.5 m³ and effectively control the dispersion and explosion risks of the propane gas cloud, the fan should be installed at a distance of no more than 2.786 m from the leak hole.

Figure 19 shows the streamline diagram under different window opening and fan positions during pressure regulator leakage, and Figure 20 presents the time series curve of the propane combustible gas cloud volume change under different window opening conditions. Based on Figures 19 and 20, it can be concluded that, in general, the fan at position b, which is closer to the leak source, disperses the propane combustible gas cloud more effectively than the fan at position d, which is farther away. During the initial stage of fan operation, the airflow is unstable in all conditions, and as the leakage continues, propane gas diffuses towards the fan at position d. At this moment, the diffusion kinetic energy of propane gas and the negative pressure energy created by the fan combine, leading to a relatively higher propane cloud dispersion efficiency when the fan is at position d. However, after 100 s of fan operation, the airflow at position b gradually stabilizes, with higher turbulence kinetic energy, and the dispersion effect becomes more noticeable, effectively reducing the volume of the combustible gas cloud. In general, the fan at position b, which is closer to the leak source, provides better dispersion performance compared to the fan at position d.

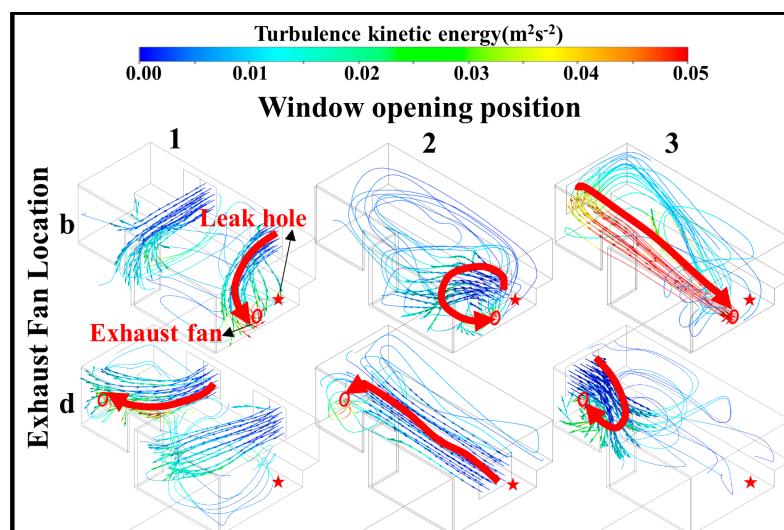


Figure 19. Flow diagrams under different window openings and fan positions when the pressure reducing valve leaks. (Exhaust fan location: b, d; Window opening position: 1, 2, 3).

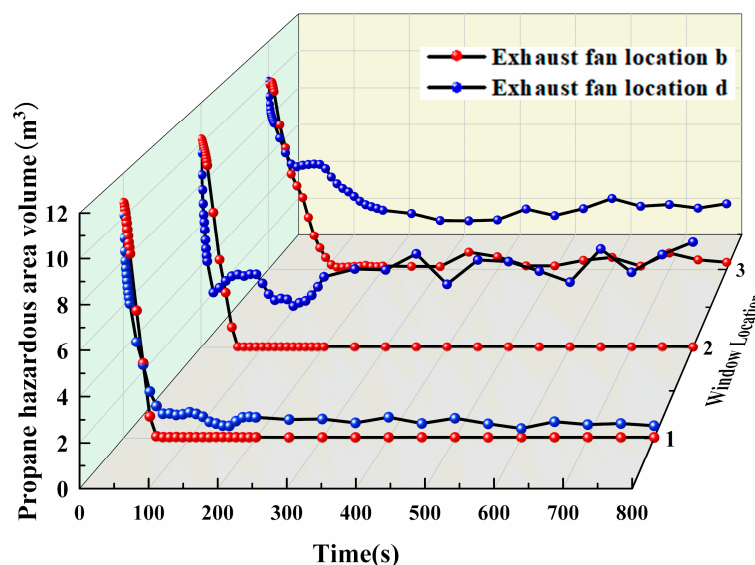


Figure 20. Change in propane combustible gas cloud volume under different fan positions.

4. Conclusions

This study carries out numerical simulations to explore the diffusion patterns of LPG leakage under various ventilation conditions. The effects of natural and forced ventilation wind speeds, fan positions, and window positions on the dispersion and dispersal efficiency of the propane combustible gas cloud were analyzed, leading to the following major conclusions:

- (1) Under natural ventilation conditions, when the window ventilation wind speed is more than 7.9 m/s, the propane concentration at the indoor alarm monitoring point remains consistently below the lower explosive limit (2.1%). There is a logarithmic relationship between wind speed and propane combustible gas cloud volume. Within the wind speed ranges of 1.5–3.3 m/s and 7.9–10.7 m/s, a small increase in wind speed can significantly reduce the volume of the combustible gas cloud (97.2% and 95.05%, respectively), effectively reducing the explosion risk of leaking propane;
- (2) Under forced ventilation conditions, at lower air exchange rates (5.98 to 10.6 times/h), the turbulence kinetic energy of the airflow is weak, and the dispersion effect on the combustible gas cloud is poor. In contrast, higher air exchange rates (22.1 times/h, 24.3 times/h) effectively increase the airflow speed, enhance the turbulence kinetic energy, and reduce the explosion risk. Once the air exchange rate reaches 22.1 times/h, further increases in exchange rate no longer effectively reduce the volume of the combustible gas cloud. Taking all factors into account, it is recommended to choose an air exchange rate of 22.1 times/h for houses with a similar confined space size.
- (3) When the window opening is at position 1, the exhaust airflow path of the fan is the shortest and the turbulence kinetic energy is the highest, which makes the dispersion effect of the fan the most obvious. The distance of the fan leakage source is exponentially increased with the volume of propane combustible gas cloud. To ensure that the volume of the combustible gas cloud does not exceed 0.5 m³, and to effectively control the diffusion and explosion risk of the propane gas cloud, the fan should be installed within 2.786 m from the leak hole. In practical applications, it is suggested to place the fan close to the potential leak source to maximize the reduction in the volume of the combustible gas cloud.

The research results improve the quantitative understanding of the LPG leakage dispersion process in commercial kitchens, not only providing data support for kitchen ventilation design, but also providing a reference for the ventilation design of LPG-use locations.

5. Future Work

These findings improve the quantitative understanding of LPG leakage dispersion in commercial kitchens, and provide guidance for ventilation system design. Future work may focus on the following: (1) Studying the influence of multi-source leakage, the direction of external wind and the mass flow velocity on the formation and diffusion of gas clouds; and (2) expanding the model to outdoor or semi-confined environments to ensure broader applicability in urban fire safety assessments.

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