

# Research on Numerical Simulation of Gas Migration Patterns during Gas Leaks in Underground Utility Tunnels

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## Abstract

This study aims to investigate the gas migration behavior during a gas leakage incident in the underground pipe gallery's gas chamber. A geometric model incorporating supports was developed using Fluent numerical simulation software, allowing for an examination of how key factors such as leakage velocity and ventilation conditions influence gas diffusion. The findings indicate that the movement of gas within the pipe gallery begins to stabilize approximately 10 seconds after a leakage event occurs. Under natural conditions, ring vortices form on both sides of the gas gallery; conversely, under ventilated conditions, a counterclockwise vortex develops above the gas pipe. The area of methane accumulation varies with different ventilation scenarios during a leak. In natural conditions, methane primarily establishes a stable circulation pattern on the right side of the pipe gallery, while some is entrained by airflow on its left side and remains trapped; under ventilated conditions, methane accumulates in a circulation zone at the lower right corner of the pipe gallery and adjacent to support structures where it cannot be expelled. As leakage velocity increases, under natural circumstances, the volume fraction of methane rises from 11.17% to 23.38%, reflecting an increase of 12.21%. In contrast, under ventilated conditions, this fraction grows from 1.81% to 3.01%, marking an increase of 1.20%.

## Keywords

Fluid dynamics; Fluent numerical simulation; Gas leakage; Comprehensive pipe gallery; Gas migration.

## 1. Introduction

A comprehensive pipe gallery refers to an underground tunnel space that integrates engineering pipelines such as gas, heating, power, communication, and water supply and drainage. Among them, the gas chamber, as a special compartment for transporting flammable and explosive media in the comprehensive pipe gallery [1], its ventilation treatment and emergency measures are directly related to the overall safe operation of the pipe gallery[2]. Previous studies have shown that in narrow channels, the airflow itself is prone to being restricted. When gas leakage occurs, the gas flow will experience diversion, convergence and other situations, forming a complex flow field[3].In some areas, vortices and stagnant flow phenomena are likely to occur, further deteriorating the ventilation effect and affecting the discharge of gas and the entry of fresh air [4].The existing research objects on gas leakage have not yet taken into account the gas pipe support structure inside the gas chamber, ignoring the blocking effect of the support on gas flow migration. Therefore, this study establishes a physical model that is more in line with engineering practice, taking the entire gas chamber as the research object, and comprehensively considering conditions such as ventilation conditions and gas leakage wind speed, to study the gas leakage law including the support structure inside the gas chamber. It has guiding significance for formulating prevention and control measures for gas leakage accidents in comprehensive pipe galleries.

## 2. Numerical Simulation

### 2.1. Mathematical model of gas diffusion

Gas leakage accidents are generally caused by the formation of leakage holes in gas pipes due to rust[5], impact and other reasons. The type of gas leakage studied in this article is small hole leakage. Small hole leakage refers to the gas leakage process where the diameter of the leakage hole is less than 20mm. Due to the small hole diameter, when there are no tributaries or other leakage holes above the leakage opening, if the friction loss and along-the-way resistance loss of the gas pipeline are not taken into account, the gas leakage flow at this time is relatively large. The following assumptions are made regarding the leakage process of the small hole:

- (1) Seamless steel pipes are commonly used as materials for gas pipelines and have a certain wall thickness.
- (2) Its leakage port is similar to the nozzle port. Due to the smaller diameter of the leakage port and the higher flow rate, its flow process is regarded as an adiabatic process of the compressible gas.
- (3) Its flow process satisfies the Euler equation of motion for univariate gas flow.
- (4) Regard gas as an ideal gas and satisfy the equation of state of an ideal gas.

According to the above assumptions, the leakage process of the small hole can be expressed as:

$$\frac{P}{\rho^k} = C \quad (1)$$

$$\frac{dP}{\rho} + udu = 0 \quad (2)$$

$$\frac{P}{\rho} = RT \quad (3)$$

In the formula,  $P$  represents absolute pressure, Pa;  $\rho$  represents the density of gas, in  $\text{kg}/\text{m}^3$ .  $u$  represents the cross-sectional flow velocity, in  $\text{m}/\text{s}$ ;  $R$  is the gas constant of the gas,  $519 \text{ J}/(\text{kg}\cdot\text{K})$ ;  $C$  represents a constant;  $T$  represents the gas temperature, K;  $k$  represents the adiabatic index of gas, 1.29.

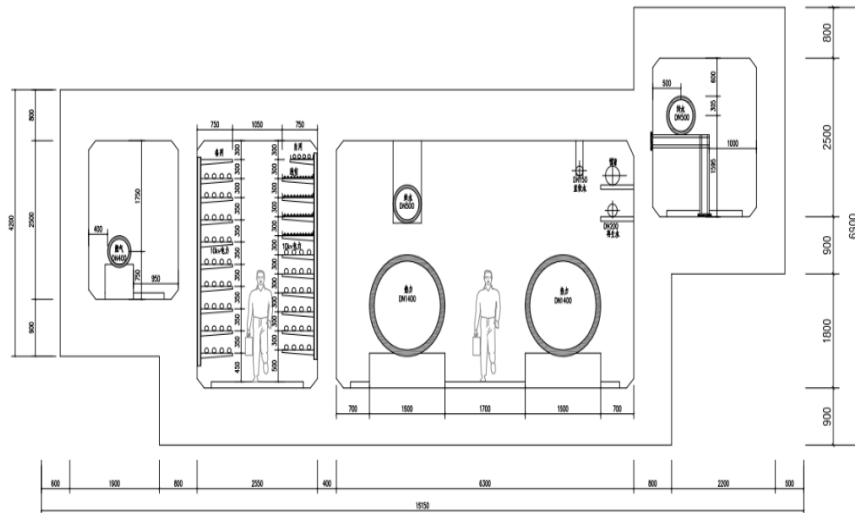
### 2.2. Construction of geometric model

According to the provisions on the structural dimensions of underground utility tunnels in the "Technical Code for Urban Comprehensive Utility Tunnel Engineering" [6,7], the standard cross-section of underground comprehensive utility tunnels is shown in Figure 1. As the gas chamber is isolated from other gases in other Spaces, a numerical simulation geometric model is constructed based on the gas chamber in the underground pipe gallery. The model and grid division are shown in Figure 2. The gas chamber is 1.75 meters high and 2.5 meters wide. The diameter of the gas pipeline is 0.4 meters. The leakage port is located directly above the center of the gas pipe, with a diameter of 0.01 meters. The support under the pipe is 0.6 meters high and 0.3 meters wide. There are openings of 0.25 meters in length at the upper left and upper right corners of the model respectively, which are used for ventilation conditions.

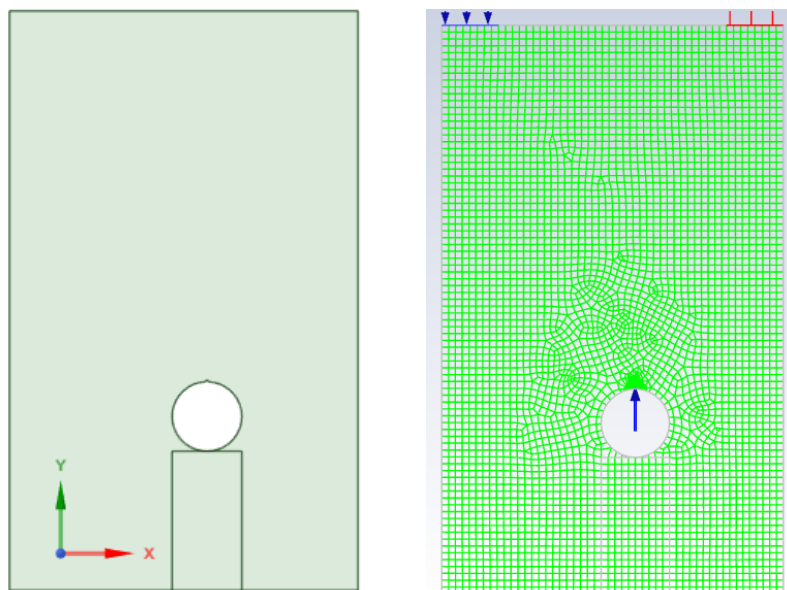
### 2.3. Boundary condition

After determining the solver, reasonable boundary conditions are the key to studying the leakage and diffusion law of gas pipelines in the comprehensive pipe gallery. In this paper, the boundary conditions mainly include fluid inlet, outlet, wall surface and other conditions. The gas pipeline leakage port and the air inlet in the upper right corner of the model are taken as

the fluid outlet boundary, with the boundary type being the free outflow boundary. The upper left corner is set as the fresh air inlet boundary, with the boundary type being the wind speed boundary. The gas pipeline leakage port is set as the methane gas inflow boundary, with the boundary type being the flow velocity boundary.



**Figure 1.** Schematic diagram of the standard section of the underground utility tunnel



(a) Geometric model diagram      (b) Grid division diagram

**Figure 2.** Schematic diagram of the numerical simulation model

### 2.4. Simulation working condition scheme

The migration law of gas is greatly influenced by the gas leakage rate and whether there is ventilation. Therefore, the gas migration under natural conditions and ventilation conditions is simulated respectively.

The leakage rates are 5 m/s, 6 m/s, 8 m/s, 10 m/s, and 12 m/s respectively. The ventilation rate of fresh air flow under natural conditions is 0 m/s. Under ventilation conditions, the fresh air flow velocity is 5 m/s, with a total of 10 simulated working conditions. The scheme design is shown in Table 1.

**Table 1.** Simulation Working Condition Scheme Table

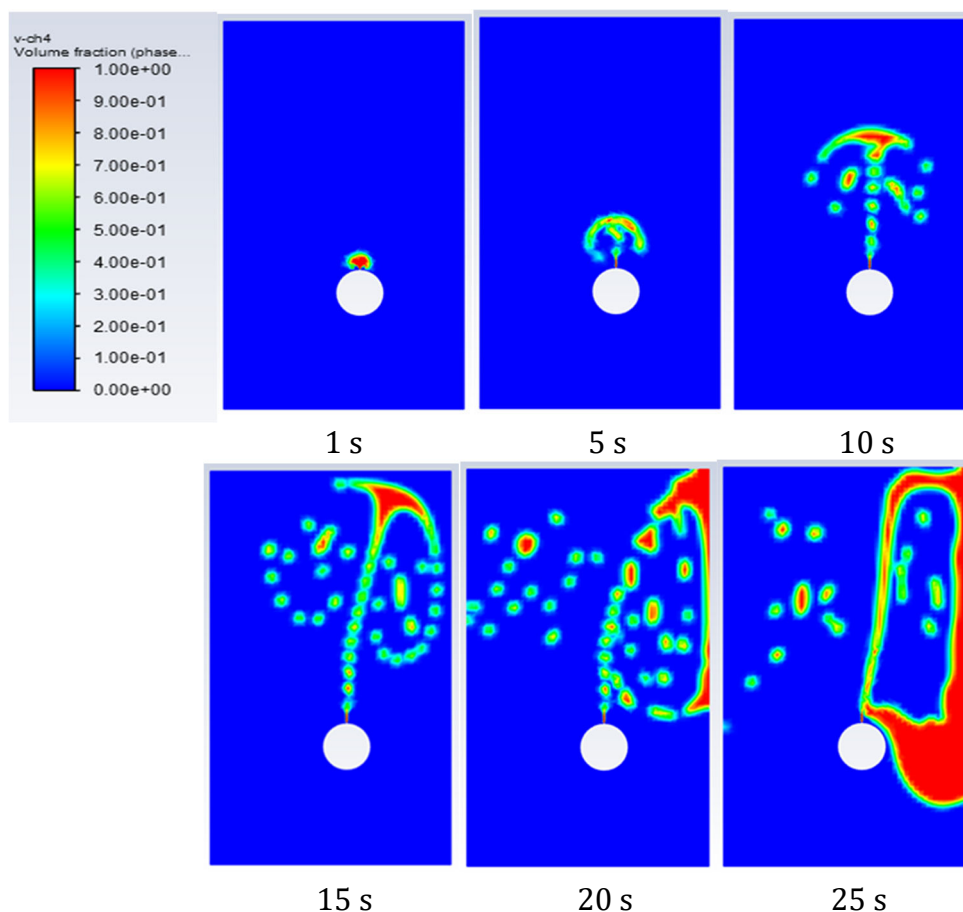
Working condition number	Gas leakage rate	Ventilation
1	5 m/s	NO
2	6 m/s	NO
3	8 m/s	NO
4	10 m/s	NO
5	12 m/s	NO
6	5 m/s	YES
7	6 m/s	YES
8	8 m/s	YES
9	10 m/s	YES
10	12 m/s	YES

### 3. Simulation Results

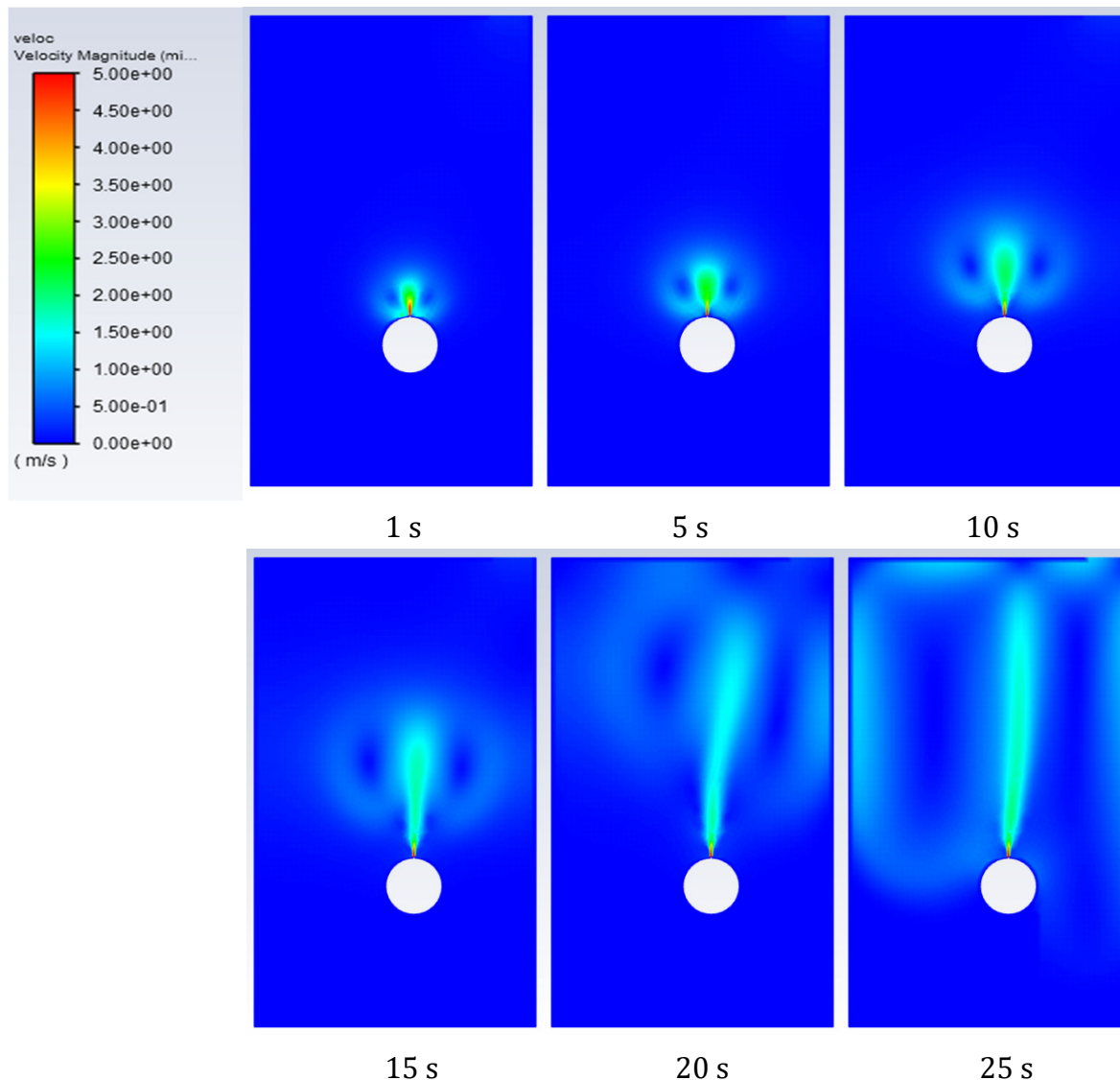
Among the above 10 working conditions, there are two key variables: the gas leakage rate and the presence or absence of ventilation conditions. The greater the gas leakage rate, the more methane volume is injected into the pipe gallery per unit time, thus having a greater impact on the proportion of methane volume. The establishment of ventilation conditions directly increases the number of fluid intakes in the model. Fresh air flow will drive methane gas to generate greater kinetic energy, affecting the spontaneous diffusion behavior of methane under natural conditions. Therefore, this factor mainly influences the gas migration law during gas leakage.

#### 3.1. The law of gas migration during gas leakage

(1) The law of gas leakage under natural conditions



**Figure 3.** Cloud map of the evolution of gas volume fraction under natural conditions



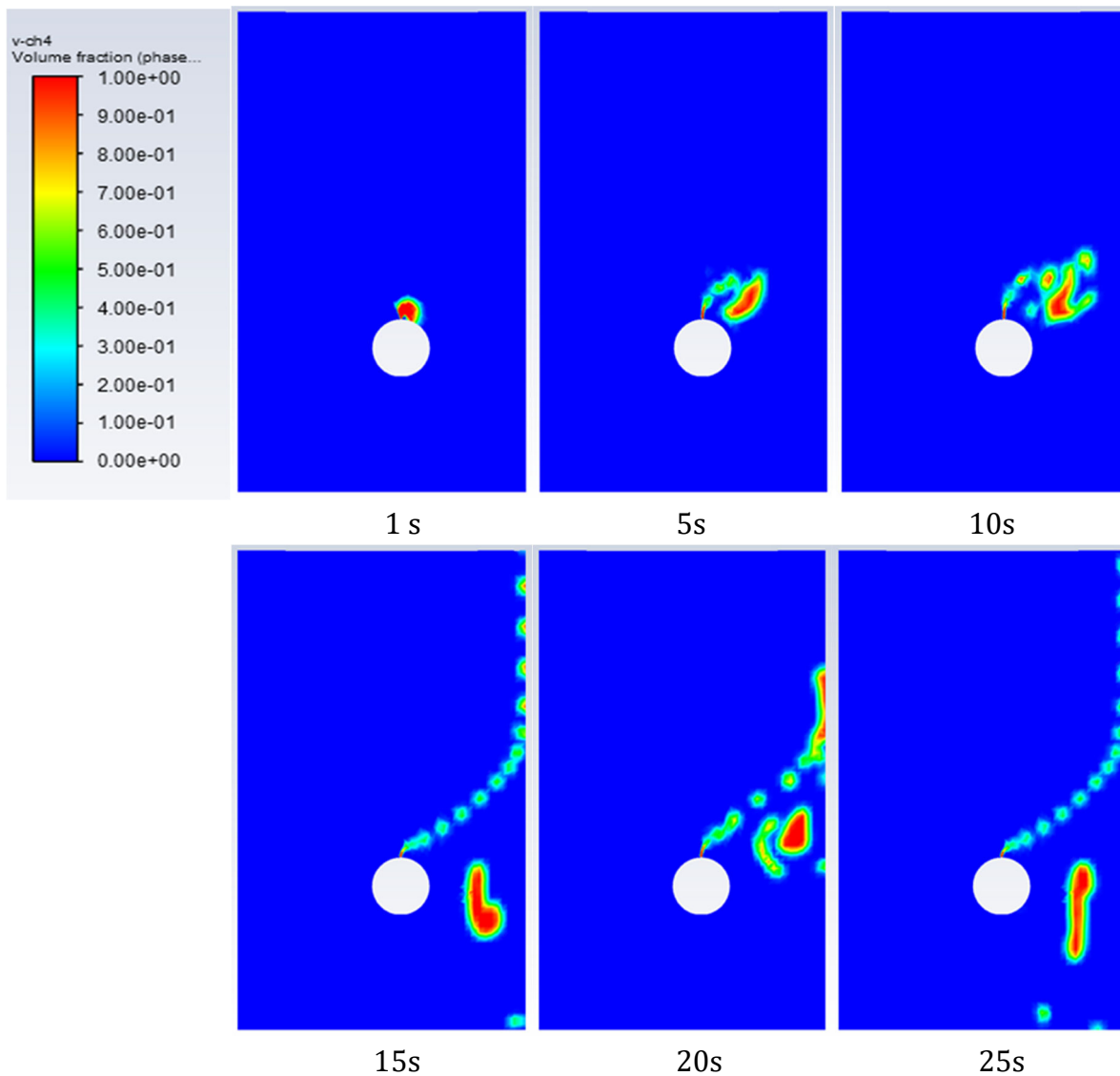
**Figure 4.** Cloud map of gas flow velocity evolution under natural conditions

Under natural conditions, a gas leak forms a distinct mushroom-shaped jet within 1 second: a narrow, high-velocity central core expanding into a broader, slower outer cloud, constrained by jet inertia and cabin space. For the first 10 seconds, the flow follows stable patterns, with the mushroom shape enlarging while retaining its core structure.

Notably, a ventilation opening in the model’s upper right corner generates negative pressure, subtly shifting gas migration rightward and altering the mushroom’s symmetry. By 15 seconds, the gas front hits the right wall; constrained by this boundary, flow lines deflect sharply, adhering to the wall in regular circulation instead of expanding freely.

By 25 seconds, a stable vortex forms on the right: faster flow at its center, slower, more turbulent motion at the edges. This process illustrates complex hydrodynamics in confined spaces, showing interactions between jet inertia, boundaries, and ventilation. Results confirm gas initially jets upward, then redirects due to tank/cabin barriers and ventilation-induced pressure gradients, forming the right-side vortex.

(2) Gas leakage rules under ventilation conditions



**Figure 5.** Cloud map of the evolution of gas volume fraction under ventilation conditions

Under ventilation conditions, the volume fraction distribution and diffusion rate of methane in the comprehensive pipe gallery exhibit significant time-varying characteristics. Under the dominant effect of the ventilation airflow, the leaked gas is carried along by the airflow at the initial stage, forming an irregularly shaped cloud-like air curtain and rapidly shifting to the right. As the diffusion process continues to advance, the air mass undergoes morphological reconstruction after colliding with the right wall, transforming into a point-like diffusion mode centered on the contact point of the wall. Under the combined effect of the ventilation airflow and the wall boundary layer, the gas gradually forms a stable vortex structure in the lower right area of the cabin. The formation of this vortex not only accelerates the diffusion and mixing of the gas but also changes the spatial distribution pattern of the gas concentration inside the cabin.

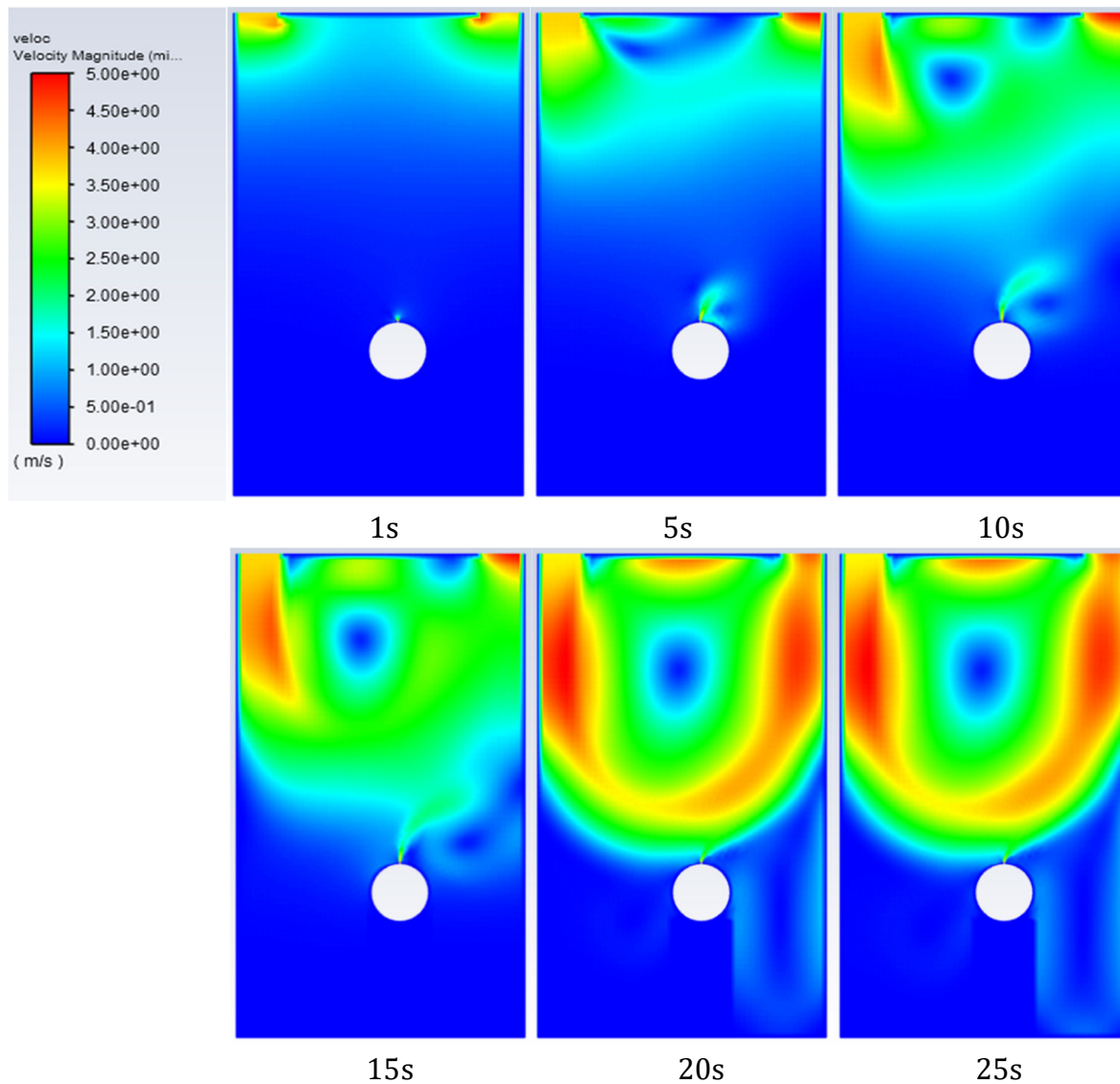


Figure 6. Cloud map of gas flow velocity evolution under ventilation conditions

### 3.2. The change in gas concentration during a gas leak

The FLUENT software has built-in surface and volume cumulative integration functions[8], as shown in Figure 7.

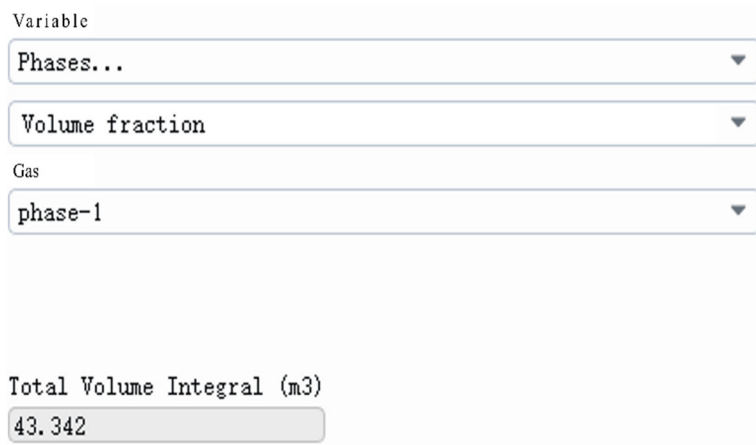


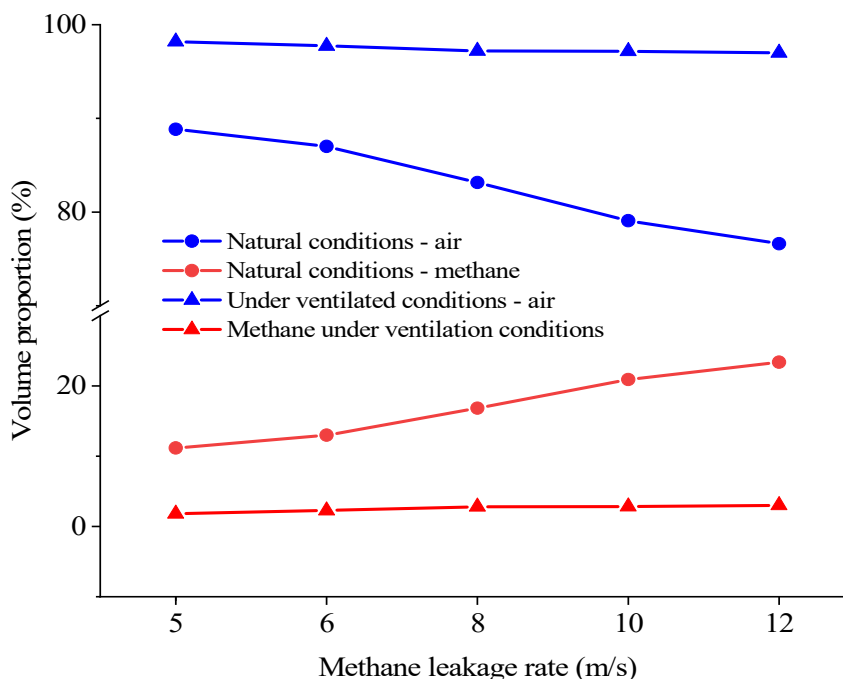
Figure 7. Schematic diagram of gas volume integral

When the gas movement laws under various working conditions are stable, the volumes of air and methane in the pipe gallery are statistically analyzed, and the proportion of each volume is calculated. The calculation results are shown in Table 2.

**Table 2.** Statistics of the volume proportion of each gas in the pipe gallery after gas leakage

Scheme Number	Proportion of fresh air flow	The proportion of leaked gas	Remarks
1	88.83 %	11.17 %	5/0
2	87.01 %	12.99 %	6/0
3	83.15 %	16.85 %	8/0
4	79.08 %	20.92 %	10/0
5	76.62 %	23.38 %	12/0
6	98.19 %	1.81 %	5/5
7	97.73 %	2.27 %	6/5
8	97.20 %	2.80 %	8/5
9	97.17 %	2.83 %	10/5
10	96.99 %	3.01 %	12/5

A line graph was drawn based on the proportion of gas volume in each working condition, as shown in Figure 8.



**Figure 8.** Line chart of the volume proportion of each gas under different working conditions

It can be known from Table 2 and Figure 8 that as the gas leakage rate increases, the concentration of methane in the pipe gallery will rise after the gas stabilizes. When the methane leakage rate increases from 5 m/s to 12 m/s, the volume proportion of methane under natural conditions increases from 11.17% to 23.38%, with an increase of 12.21%. Under ventilation conditions, the volume proportion of methane increased from 1.81% to 3.01%, with an increase of only 1.20%. Therefore, relatively speaking, the rule that the concentration of methane

increases with the increase of methane leakage rate under natural conditions is more significant.

#### 4. Conclusion

About 10 seconds after a gas leakage accident occurs in the pipe gallery, the gas movement pattern inside the pipe gallery begins to stabilize. Under natural conditions, circular vortices form on both sides of the gas pipe corridor respectively. Under ventilation conditions, counterclockwise vortices form above the gas pipe.

(2) When gas leaks, the location where methane accumulates changes with the ventilation conditions. Under natural conditions, methane mainly forms a stable circulation on the right side of the pipe gallery, and part of it is carried by the airflow on the left side of the circulation and cannot be discharged. Under ventilation conditions, methane accumulates and circulates in the lower right corner of the pipe gallery and on the right side of the support, and cannot be discharged.

(3) With the increase of gas leakage rate, the volume proportion of methane under natural conditions rose from 11.17% to 23.38%, an increase of 12.21%, and under ventilation conditions, it increased from 1.81% to 3.01%, an increase of 1.20%.

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