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# Numerical Investigation of Micro-Leakage Flow-Field of Underground Gas Wellbore

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**Keywords**

Wellbore
Micro-leakage
Flow-field
Simulation
Shape.

**Abstract**

In order to study the characteristics of micro-leakage flow field with high-pressure underground gas wellbore, the model of flow field is built. Using numerical simulation methods, the flow fields of micro-leakage are analysed. Based on computational fluid mechanics theory, the flow field distribution of different shapes of leakage orifice and different diameters of circular leakage orifice under different conditions are calculated. The velocity, pressure, mass flow and the characteristics of the flow field are analysed. The simulation results show that the larger the section of a leakage orifice is, the closer the leakage orifice shape is to circle, then the faster the gas pressure drops along the leakage orifice, the higher the gas flow velocity is.

## 1. Introduction

There are often leakages or even ruptures in underground gas wellbores because of soil corrosion, shock, etc. The leaked gas not only pollutes the environment, but also causes explosions, hurts people and damages buildings. Huge leakage accidents are caused by micro-leakage expanding gradually. So it is very important for underground gas wellbore to detect micro-leakages. [1-2]

The researchers focus on the gas diffusion after the leaks in explosion accidents firstly, and then study the characteristics of the flow field in order to get the detection methods for leakages. With the development of technology, researchers begin to study micro-leakages to prevent leakage orifices from expanding and ensure wellbore safe running. Acoustic detections for leak based on sound source characteristics of leakages and the principles of sound field distribution are widely studied and used to locate the leak position and judge the amount of leakage because of their advantages such as higher precision, sensitivity and better adaptability [3]. Parvini [4] evaluated the effects of gas leakage on soil by establishing two sub-models of near-field and far-field for a leakage pipeline, and got a comprehensive model of underground gas wellbore. Lu [5] studied the leakage theory of two-dimensional model of urban pipelines, and analyzed the pressure, velocity and temperature of gas in steady-state and transient state of the leakage flow field of the model, which shows that for the steady-state leakage in a certain range, the gas flow velocity increases with the increasing of the pressure and the diameter of the leakage orifice. For transient leakage, the time from the leak occurring to the flow being stable is very short and then negligible. However, due to the limitations of the two-dimensional model, Martins [6] used three-dimensional grids in the leakage model to calculate and analyze changes of the flow and the pressure in the transient state of the leakage under high-pressure by computational fluid dynamics (CFD), especially analyzed the flow on the center axis and the wall of leakage orifice, which is verified by experiments. Huang et al [7] studied the gas diffusing distribution of the square, rectangular leakage orifice and the basic characteristics of the spray flame by simulating the leakage model of natural gas wellbore, but they did not further analyze the leakage characteristics. Shi [8] simulated the leakage of the liquid pipeline with different leak width, obtained the rules of the flow field distribution with the leak width changing and its influence on the sound source.

Above all, at present the researches on micro-leakage focus on the followings: diffusion of the gas when leaking, the influence of leakage diameters and pressure on the flow field, methods and principles of acoustic leak detection, and so on. While the researches on collection and deal with the generation mechanisms of sound wave from the leakage are paid very little attention [3], and the effect of different sectional areas of micro-leakage orifice and its different shapes on the flow field are seldom discussed. The characteristic of flow field of leakages is very useful for leak-acoustic detection, which is also the key to the detection technology of micro-leakage [9].

## 2. Theory and Modelling

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When micro-leakage occurs in a gas wellbore, high-pressure gas forms a strong turbulence because of the pressure difference between that in and outside the wellbore and the interaction between the gas and the wellbore wall, which forms a jet flow field around the leakage orifice. The unstable interaction force caused by the interaction between the surface of the object and the fluid is called the dipole sound source. The quadrupole sound source is produced by the turbulence of the fluid itself.

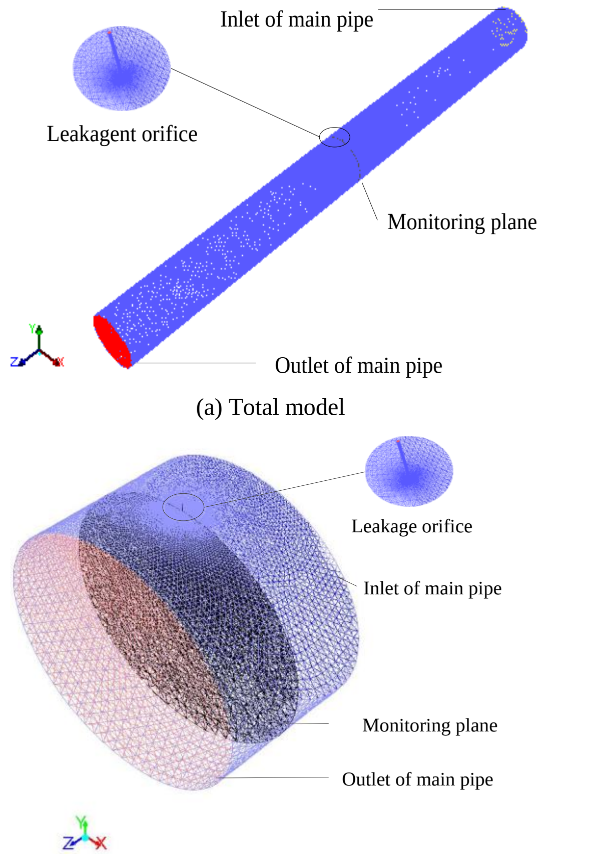
As there are high pressure and high flow velocity in the gas wellbore, when a leakage occurs, gas is sprayed at high flow velocity from the leakage orifice under the pressure difference inside and outside the wellbore, and the high-velocity jet flow area is formed near the leakage orifice. The flow state inside the wellbore is very complicated, so it is necessary to make reasonable assumptions about the flow. The main body is in the turbulent state, and the influence of the gas laminar flow and the sound field on the sound source can be neglected to study the ideal sound source during the leakage process. The analysis of the gas flow state, the Lighthill theory and the FW-H equation show that the sound sources of the wellbore leakage is from the compressibility of the gas and the turbulence pulsation caused by the Reynolds stress or the shear stress due to the unstable flow of the high velocity [10].

According to the definition of the above-mentioned sound source types, the monopole source is produced by the change of the mass flow of the fluid when the wellbore leaks. The dipole source formed by the coupling of high-velocity compressible gas and wellbore wall, and the quadrupole sound source is produced by turbulent pulsation caused by high-velocity flow near the leakage orifice, including a large number of vortices and a sharp mixture with static fluid outside the wellbore, which resulting in a large velocity difference at the boundary layer to form the jet noise. For the micro-leakage of wellbore, the motion of wellbore wall is not involved in the leakage process, and the mass flow of the leakage gas remains unchanged, so the monopole sound source can be ignored. A dipole source is produced by the friction of the gas with high-velocity and the wellbore wall. The gas flow velocity is accelerating in the leakage orifice by the pressure difference, and the turbulence pulsation of the gas itself produces a quadrupole sound source.

In this paper, the $k$-$\varepsilon$ turbulence model is used to simulate the flow field. The $k$-$\varepsilon$ model obtains the values of the turbulent kinetic energy $k$ and the dissipation rate $\varepsilon$ by solving the turbulent kinetic energy equation and the turbulent dissipation equation.

The leakage of gas wellbore is a fast and complete process, which completes instantly from the start of leaking to form a steady flow field [12]. Before the theoretical analysis and simulation, there will be some assumptions: it can be considered that when the wellbore leaks, the flow field in the wellbore begins to change, the gas will eject at a high velocity along the leakage orifice under the pressure difference.

According to the parameters of the gas wellbore, the simulation model is built shown in Figure 1. The length of the main wellbore in the model is 1192 mm, its diameter is 104 mm, and the length of leakage orifice is 5 mm, which is consistent with the thickness of wellbore wall used in the test stand. The divided grid is encrypted to improve the simulation accuracy. In order to study the influence of different diameters on the flow field in the leakage process under the same conditions, the diameters of the circular leakage orifice are set to four types, which are 0.17 mm, 0.3 mm, 0.4 mm and 0.47 mm respectively. The shapes of the leakage orifices include circle, gap, triangle and square. The sections of other leakage shapes are equal to that of the circular leakage orifice with its diameter of 0.3 mm, among which the length is 1.41 mm, the width is 0.05 mm of the gap shape, and the side length of the triangle is 0.404 mm, the side length of square is 0.266 mm, shown in Table 1.




(a) Total model

(b) Zoom of model

**Figure 1.** The simulation model of micro-leakage in a wellbore

**Table 1.** Parameters of different leakage orifice shapes

| No. | Name | Shape and parameters |
|---|---|---|
| 1 | Gap | 0.05mm, 1.41mm |
| 2 | Triangle | 0.404mm, 0.404mm, 0.404mm |
| 3 | Square | 0.266mm, 0.266mm |
| 4 | Circle | 0.3mm |

The flow field part is only used to simulating and solving the steady state of leakage because that the time variation of sound sources from the initial leakage to the steady process is ignored in simulation. The standard $k$-$\varepsilon$ turbulence model is used to calculate and analyse the distribution of pressure and velocity in the leakage flow field. Parameters of the steady state flow field are used as initial conditions in the sound field. The distribution of sound source in the leakage process is analysed by using the broadband sound source model. The medium in the wellbore is compressed ideal nitrogen, and that outside the wellbore is atmosphere. The boundary conditions of simulation are as follows: the inlet boundary condition of the wellbore is pressure inlet, the outset boundary condition of the wellbore and that at the end of the leakage orifice is the pressure outlet, and the rest surfaces are the default physical wellbore walls.

## 3. Results and Discussion

The simulation model of wellbore is three-dimensional. The surface of the model is standard wellbore wall, which cannot reflect the internal flow field, so the monitoring plane is set up as a monitoring plane to describe the distribution of the flow field parameters, shown in Figure 1(b). Monitoring planes of triangular, square and circular leakage are parallel to the inlet and outlet planes of the wellbore, across the inside of the wellbore and the leakage orifice. The monitoring plane of gap leakage is perpendicular to the outlet plane of the wellbore, and through the inside of the wellbore and the leakage orifice, shown in Figure 2. The monitoring plane itself does not affect the flowing inside the wellbore, reflects the distribution of flow field parameters inside the wellbore and the gap leakage orifice.

Figure 3 and Figure 4 are the distribution graphs of velocity and pressure in the flow field of a wellbore leakage, the pressure difference between outside and inside of the monitoring plane in the wellbore model with circle leakage is 3 MPa and the diameter of the leakage orifice is 0.3 mm. The area around the leakage orifice is enlarged to show the changes of parameters more clearly.

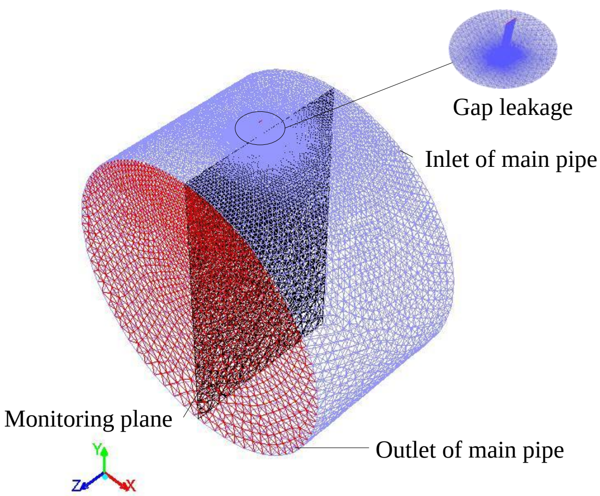
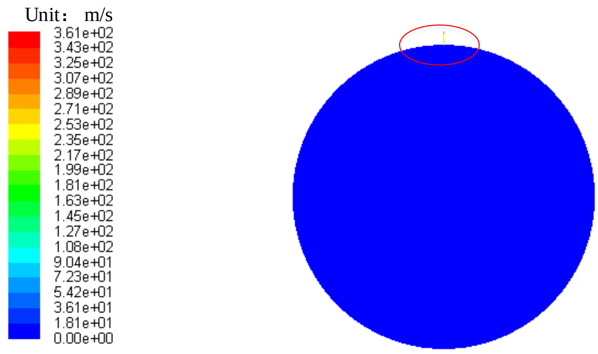
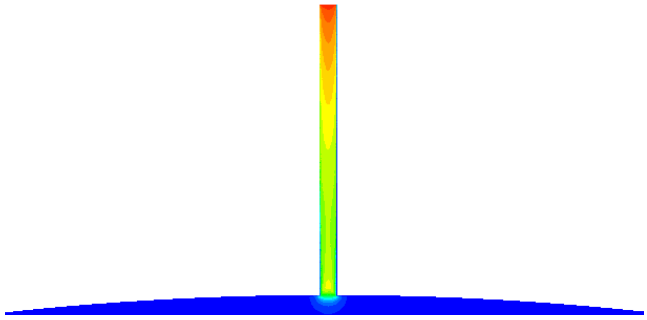



**Figure 2.** The simulation model with gap leak




(a) Total



(b) Zoom

**Figure 3.** Velocity distribution in the monitoring plane of a circular leakage orifice

In Figure 3, the colour scale on the left is the velocity distribution range of the wellbore, and the different colors correspond to the different velocities. The circle in the middle is the monitoring surface of the main wellbore. The right side is the local area of wellbore leakage orifice. The gradient of the color scale on the left from blue to red indicates that the flow velocity is increasing. The colour of main wellbore is almost all blue, and the color change is happened only near the leakage orifice. The gradient of color reaches the maximum at the joint of the wellbore and the leakage orifice, which decreases first and then increases along the leakage orifice from inside to outside the wellbore. It can be concluded from the Figure 3 that there is little effect on the main wellbore of the flow field change caused by leakage, and almost no obvious disturbance of internal flow in the wellbore. Due to the velocity gradient is the largest around the leakage orifice and the joint of the wellbore and the leakage orifice, so there is a big change of the flow field. The gas flow velocity increases along the leakage orifice and reaches the maximum 361 m/s at the top of the circular leakage orifice, which is equal to supersonic velocity.

In the circular leakage orifice, the gas flow velocity increases along with the distance of it from the wall of leakage orifice increasing, and reaches the maximum value at the axis of leakage orifice. That is because gas brings relative displacement with the wellbore wall, and the viscosity of the gas causes a shear stress between gas and the wall, thus a velocity boundary layer near the wellbore wall is formed and the gas flow velocity reaches the maximum at the axis of the circular leakage orifice.

In Figure 4, the colour scale on the left is the pressure distribution range of wellbore and the different colours correspond to the different pressures. The blue part shows the area with low pressure, and the red part indicates the high pressure. The gradient of the colour scale on the left from blue to red indicates that the pressure is decreasing. The main wellbore is almost all red, and there is colour change only near the leakage orifice. The gradient of colour reaches the maximum at the joint of the wellbore and the leakage orifice, which decreases first and then increases along the leakage orifice from inside to outside of the wellbore. The colour is light blue at the top of the leakage orifice, which shows that the leakage under this condition has little effect on the internal pressure of the main wellbore, and could be neglected. The gas pressure gradually decreases along the leakage orifice, and its maximum gradient lies in the joint of the wellbore and leakage orifice. Finally gas pressure reaches to 0.501 MPa when the gas going out of the leakage orifice, which is still higher than the atmospheric pressure. According to the continuity equation, the gas flow velocity gradually increases along the leakage orifice and reaches the maximum gradient at the joint of the main wellbore and leakage orifice, which verifies the changes of the flow velocity mentioned above.

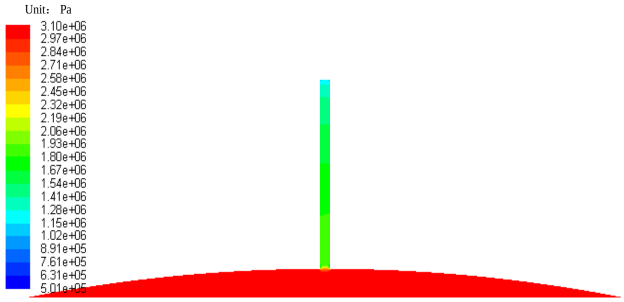
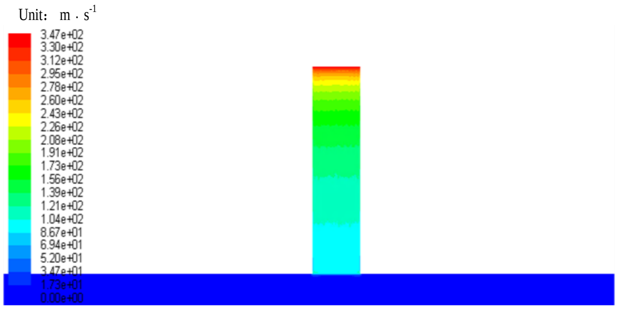
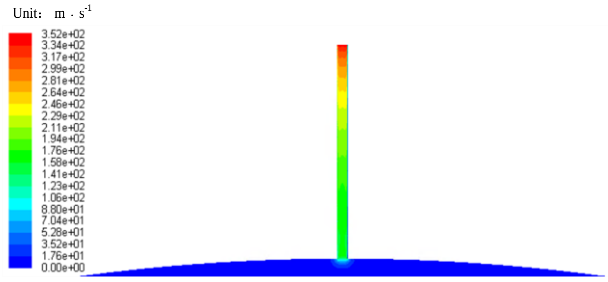



**Figure 4.** Pressure distribution in the monitoring plane of a circular leakage

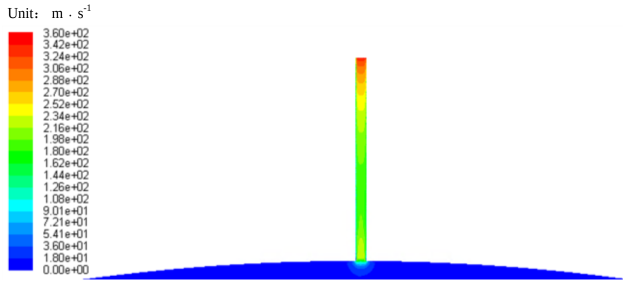
In wellbore, the leakage shapes are various because of environmental factors, so it contributes to enrich the leak detection theory to make comparative studies of the characteristics of the flow field in the different leakage shapes. Figure 5 shows the flow velocity distribution of leakage orifices with different leakage shapes including gap, triangle and square in the same conditions. The diameter of the circular leakage orifice is 0.3 mm. The other shapes of the leakage orifice are with the same section of the circular leakage orifice. In the same conditions, distribution of flow velocity and pressure along the axis of leakage orifice with different leakage shapes are shown in Figure 6.




(a) Gap

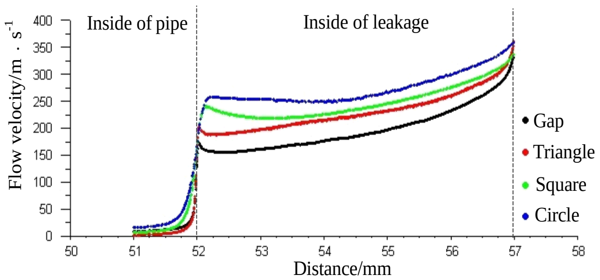



(b) Triangle

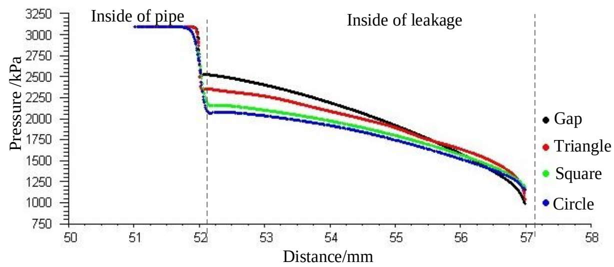



(c) Square

**Figure 5.** Comparison of flow velocity distribution of different leakage orifice shapes




(a) Flow velocity




(b) Pressure

**Figure 6.** Distribution of flow velocity and pressure along the axis of leakage orifice with different leakage orifice shapes

According to Figure 5 and Figure 6, we can find that:

(1) The gas flow velocity is small near the leakage orifice inside the wellbore, and increases rapidly when the gas enters the leakage orifice. The flow velocity in a wellbore with circular leakage orifice is the largest, while it is minimal in a wellbore with the gap leakage orifice.

(2) After entering the leakage orifice and reaching the maximum, the gas flow velocity will have a short descent and then gradually increase.

(3) The gas flow velocity inside the leakage orifice is increasing as a whole. The gas flow velocity increases at the top of the leakage orifice in the way of acceleration, and continues to accelerate after reaching the sound velocity. Finally the gas flows out at the supersonic velocity.

(4) The outlet pressure at the top of all leakage orifices is still higher than the atmospheric pressure.

## 4. Conclusions

(a) When flowing into the leakage orifice from the wellbore, the gas flow velocity increases and the pressure gradually reduces along the leakage orifice, and both of their gradients reach the maximum at the joint of the wellbore and the leakage orifice.

(b) After the gas enters the leakage orifice, the flow velocity is increasing and the pressure is decreasing inside the leakage orifice as a whole. However, due to the inertia of the gas, the gas flow velocity is locally decreased and the pressure is locally increased in the necking, and the vortex motion is generated. Then the flow velocity and pressure keep the original trend when out of the leakage orifice, where the pressure of the gas is still higher than the atmospheric pressure. So the gas continues to expand after flowing into the atmosphere, the flow velocity continues to increase, and the pressure continues to decrease until it equals atmospheric pressure.

(c) Under the same conditions, the flow velocity of the circular leakage orifice is the largest, followed by the square, triangle, and that of the gap leakage is the minimum. Therefore, the closer the shape is to the circle, the larger the flow velocity is.

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