Simulation Analysis of Leakage Flow Field of T-Type Three-way Gas Pipeline

Tao Lu [1, a], Haobin Wen[1, b], Kankui Ou [2, c], Xingxing Zhang [1, d]

[1]School of Mechanical Engineering, Sichuan University of Science and Technology, Yibin 644000, China

[2]Yibin City China Resources Gas Co., Ltd.3, China

[a]948696961@qq.com, [b]595546316@qq.com, [c]370183379@qq.com, [d]2573694023@qq.com

Abstract

During the operation of gas pipelines, due to material defects, external corrosion, third-party damage and other factors, it is easy to cause damage to the pipeline and cause a large amount of gas leakage. The three-way pipe is an indispensable component in the pipe network. Its flow characteristics are obvious. The change of downstream flow state will inevitably cause changes in the pipeline nodes. Therefore, it is particularly important to study the internal flow field change law of the gas three-way pipe under the leakage of large holes. According to the four types of import and export combinations in the gas pipeline network, five pipeline leakage models are established, the FLUENT software is used to simulate and analyze the flow of the pipeline under sudden leakage, and the simulation results are verified by theoretical calculations. The results show that after a large-hole leak occurs, the pressure change trend in the tee pipe is roughly the same. The pressure in the branch pipe where the leakage point is located is lower than the initial pressure value in the pipe. The pressure wave generated by the leak propagates along the pipeline to the tee node, producing obvious leakage signals. The research results have certain reference significance for improving the accuracy of pipeline leak detection, reducing detection costs, and developing leak detection devices.

Keywords

FLUENT; Three-way pipeline; Natural gas transmission; A broken line.

1. Introduction

The pipeline may be perforated, cracked or even broken due to factors such as external corrosion, material defects, material aging, poor installation quality or third-party damage, causing a large amount of gas leakage [1]. As shown in the following figure in the pipeline accident of a certain city in Sichuan in 2019, the early gas pipeline was not marked when it was landfilled, which caused the pipeline to be drilled by the drilling rig under construction. The accident not only caused a great waste of energy, but also the natural gas itself is flammable, Hazards such as explosiveness have also seriously threatened the safety of residents' lives and property. At present, domestic and foreign scholars focus on the changes of flow field and sound field under small hole leakage. Ben-Mansour [2] analyzed the flow field and turbulence field under different leakage sizes through CFD simulation, and concluded that pipeline pressure and leakage size have an effect on leakage. The flow has a greater impact. Cuiwei [3] studied the changes in the flow field and sound field in the pipe when the leak occurred, and found that the main cause of the pressure disturbance in the natural gas pipeline is the sound source fluctuation caused by the turbulence fluctuation. Yan Mingqing [4] studied the changes in the flow field when a large crack occurred in the gas pipeline, and obtained the distribution characteristics of the pipeline flow field and the calculation results of the leakage. Hao Yongmei

[5] [6] studied the leakage of small holes in urban non-metallic pipelines through CFD simulation and experimental verification, and analyzed the characteristics of the flow field distribution at the leak outlet. The urban pipeline network is large in scale, the proportion of three-way pipes is relatively small, and the fluid state in the pipes is characteristic. Therefore, this paper selects the leakage accident in Figure 1.1 as the research object to establish a pipeline rupture model. By studying the large-hole leakage condition, the upstream T The change of the flow field in the type three-way pipe has certain reference significance for improving the accuracy of pipeline leakage detection, reducing detection costs, and developing leakage detection devices.

Fig. 1.1 Scene photo of gas pipeline failure

2. Theoretical model

Under normal circumstances, the flow of gas in the tube can establish the corresponding continuity equation, motion conservation equation, and energy conservation equation for the gas flow according to fluid mechanics. Bernoulli's equation is an energy equation for the conservation of mechanical energy. This equation can be used to accurately analyze the mechanical energy conversion of natural gas during the flow of the three-way pipe:

$$\rho g q_1\left(z_1+\frac{p_1}{\rho g}+\frac{\alpha_1 \bar{v}_1^2}{2g}\right)=\rho g q_2\left(z_2+\frac{p_2}{\rho g}+\frac{\alpha_2 \bar{v}_2^2}{2g}+h_{w1\text{-}2}\right)+\rho g q_3\left(z_3+\frac{p_3}{\rho g}+\frac{\alpha_3 \bar{v}_3^2}{2g}+h_{w1\text{-}3}\right) \tag{1}$$

In the formula, q1 is the flow rate of the inlet pipe, and q2 and q3 are the flow rate of the outlet pipe.

This research uses the RNG k-ε turbulence model. Compared with other models, this model has a stronger effect on flow problems such as large strain rate, flow separation, complex secondary flow and backflow, and can be better dealt with Flow with high strain rate and greater degree of streamline bending[7]. The calculation equations of turbulent kinetic energy and turbulent dissipation rate are expressed as follows:

The turbulent kinetic energy K equation is

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+\rho\varepsilon \tag{2}$$

The ε equation of turbulence dissipation rate is

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right)+\frac{C_{1\varepsilon}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{3}$$

Where, σ_k, σ_ε are the Prandtl number corresponding to turbulent kinetic energy and dissipation rate;θ is kinematic viscosity;αk, α_ε is the Prandtl number corresponding to the turbulent kinetic energy K and the dissipation rate of turbulent kinetic energy, $\alpha_k = \alpha_\varepsilon = 1.39$, $\eta_0 = 4.377$;G_k is the generating term of turbulent kinetic energy k caused by the average velocity gradient.$C_{1\varepsilon}$ and

$C_{2\varepsilon}$ are empirical constants, $C_{1\varepsilon}=1.42$, $C_{2\varepsilon}=1.68$;C_μ is the model coefficient, $C_\mu=0.0845$;β is the coefficient of thermal expansion, $\beta=0.012$;Eij time mean strain rate.

3. Physical model

Use solid works to establish a curved three-way pipe model without wall thickness. Taking the center of the tee as the origin of the coordinates, the size of the structure is set as shown in Figure 2.1, and the inner diameter of the pipe is $D_2=200$mm. The three-way pipe is laid horizontally. In order to make the fluid fully developed after entering the three-way pipe, the length of the branch pipe is 15 times the pipe diameter, and the main pipe is 30 times the pipe diameter, ie $L_1=3000$mm, $L_2=6000$mm. This study is aimed at the large-hole leakage model. The leakage port model is shown in Figure 2.2, and the orifice diameter is 200mm. The leakage ports of the two outlet branch pipes are both 1m away from the pipe outlet.

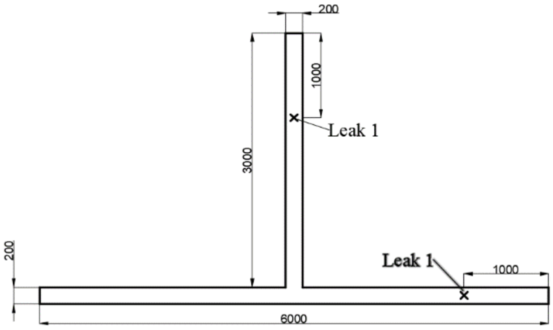

Figure 2.1 Schematic diagram of T-shaped three-way pipe structure

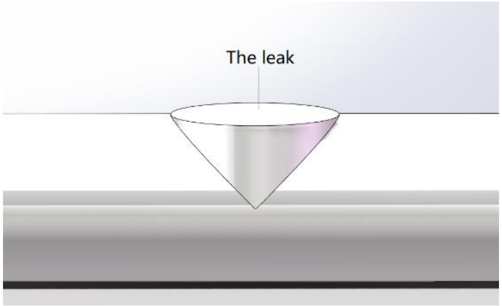

Figure 2.2 Three-dimensional solid model of the leak

4. Calculation method

Compressible air is used as the flowing medium, with a density of 1.29kg/m3. The steady-state simulation of the k-e two-equation model is used as the initial condition of the transient simulation, the calculation time is 0.4 seconds, the time step is 0.001s, and a total of 400 iterations are performed. In order to study the instantaneous change law of the flow field of the T-shaped three-way pipe in the natural gas pipeline network under the state of leakage, according to the flow pattern characteristics of the natural gas in the pipeline network, the three-way pipe can be divided into four types of inlet and outlet combinations[8]. Five kinds of leakage conditions, as shown in Figure 3.1, the direction of the arrow indicates the direction of gas flow. When the pipeline is in normal operation, the leakage port is set to the wall without slippage condition. When the transient simulation is carried out to the 0.1s, the boundary condition of the leakage port is changed from the wall to the pressure outlet, and the pressure is the standard atmospheric pressure to simulate the sudden pipeline The actual flow field change at the time of destruction.

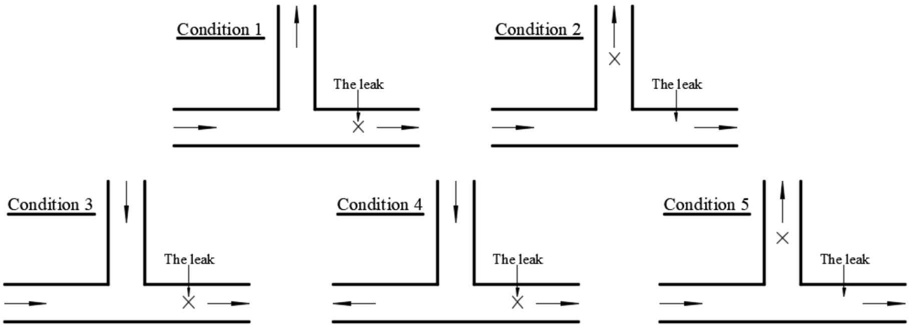

FIG. 2.3 Schematic diagram of leakage condition

5. Simulation results

The fluid medium in the tube is compressible air with a temperature of 300K. Use FLUENT software to simulate its leakage flow field and select the branch pipe axis where the leakage point is located for analysis. The inlet boundary condition is set as the pressure inlet, the pressure is slightly higher than the outlet pressure, and the size is 301KPa; the outlet boundary condition is set as the pressure outlet, the pressure size is 300KPa, and the specific settings are shown in Table 1.

Table 1 Boundary conditions

Working condition	Inlet pressure/KPa		Outlet pressure/KPa	
1	Inlet		Outlet 1	Outlet 2
	301		300	300
2	Inlet		Outlet 1	Outlet 2
	301		300	300
3	Inlet 1	Inlet 2	Outlet	
	301	301	300	
4	Inlet		Outlet 1	Outlet 2
	301		300	300
5	Inlet 1	Inlet 2	Outlet	
	301	301	300	

5.1. Flow Field Analysis of the First Leakage Condition

Set the three-way pipe as a combination of a horizontal inlet, a vertical outlet and a horizontal outlet. In the initial flow field, a large amount of fluid flows to the outlet of the straight pipe along the direction of inertial force, and a small part of the fluid flows into the vertical outlet branch pipe through the split, resulting in a similar back-step effect The flow is separated[9], forming a wide range of secondary flows and vortices. When the vertical outlet leaks, the pressure drop at the leaking outlet is the standard atmospheric pressure. According to the analysis of the transient flow field and the axis of the leaking branch pipe when the leak occurs, the upstream and downstream fluids flow to the leaking outlet under the action of huge pressure difference, and the horizontal outlet branch The natural gas in the pipe flows back, meets the fluid in the inlet branch pipe at the tee, and flows into the vertical branch pipe. At the beginning of the leakage, that is, in the 0.11s of the transient simulation, the fluid flows to the leakage port at high speed, the vortex in the vertical branch pipe almost disappears, and the low pressure state in the entire pipe produces a negative water hammer effect. In the 0.02s of the leakage, two high-speed fluids collided at the leakage port, and the positive water hammer effect caused the back pressure in the vertical outlet branch pipe to rise, and the backflow in the horizontal pipe reflowed to the horizontal outlet under the action of the pressure difference; the leakage occurred At 0.03s, the pressure of the tee pipe reaches its maximum value. The reason is that the fluid in the inlet branch pipe flows to the tee pipe at a relatively high speed under the action of high pressure difference, and then merges with the return flow in the horizontal outlet pipe again. The effective cross-sectional area of the fluid decreases. Small, the gas is compressed to convert kinetic energy into pressure energy, and the maximum pressure in the tube is about 0.33MPa. When the flow state in the vertical outlet branch pipe gradually stabilizes, the pressure change of the tee pipe also decreases. The pressure in the branch pipe where the leakage point is stabilized is lower than the initial pipe pressure value, and the size is about 0.29MPa.

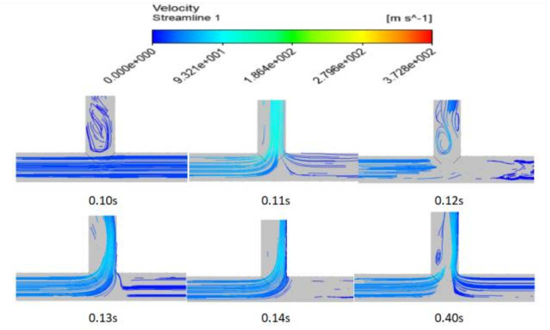

Figure 4.1 Transient speed change

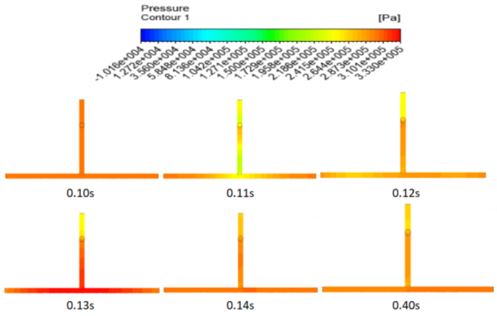

Figure 4.2 Transient pressure field change

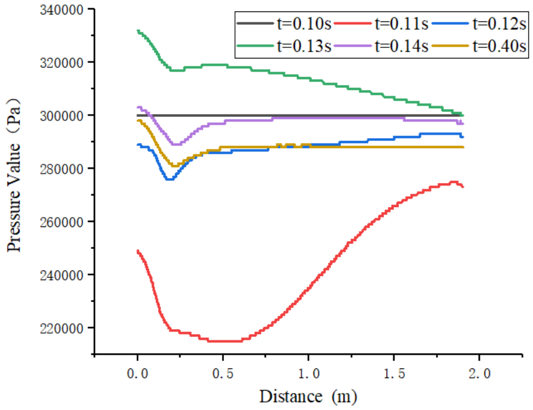

Figure 4.3 The pressure change diagram of the center line of the leaking branch pipe

5.2. Flow field analysis of the second leakage condition

The initial boundary conditions of the second leakage condition are the same as the first. Analyzing the instantaneous flow field after leakage and the change in the axial pressure of the leakage branch pipe shows that: when the horizontal outlet leaks, the fluid quickly flows out of the pipe, resulting in a low pressure state in the local pipe section. The lowest pressure reaches 0.21MPa, the entrainment effect is strengthened, and the vertical outlet branch The fluid in the pipe flows back and merges with the fluid in the inlet branch at the tee. Due to the sudden change of the flow channel and the action of centrifugal force, the merged fluid produces a relatively large scouring force on the bottom of the tube, and the existence of a pressure gradient causes a local vortex to form on the inside. In the 0.12s of the transient simulation, the high-speed flow of fluid meets at the leak hole, and the collision of the fluid produces a similar water hammer effect, which causes the back pressure in the pipe to rise, the flow velocity to slow down, and the local vortex at the tee pipe increases significantly. At 0.03s after the leak occurred, the pressure of the three-way pipe reached its maximum value, which was about 0.33MPa. As the flow field gradually stabilizes, the pressure change in the T-tube also weakens. The pressure in the branch pipe where the leakage point is in the steady state is lower than the pressure value in the pipe in the initial state.

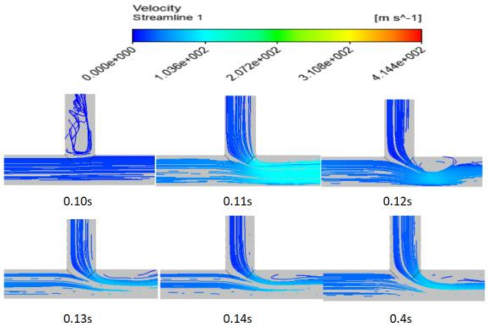

Figure 4.4 Transient speed change

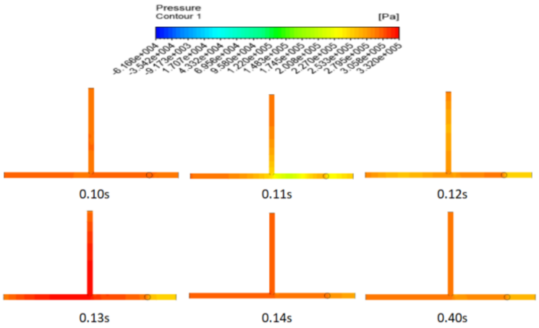

Figure 4.5 Transient pressure field change

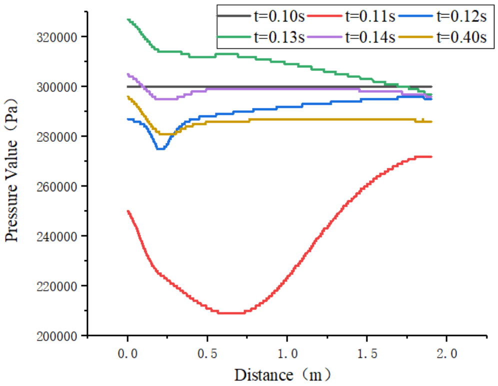

Figure 4.6 The pressure change diagram of the center line of the leaking branch pipe

5.3. Flow field analysis of the third leakage condition

The third working condition sets the three-way pipe as a horizontal inlet, a vertical inlet and a horizontal outlet. When the downstream pipeline leaks, the fluid in the outlet branch pipe quickly flows out of the pipe, causing the pressure of the local pipe section to drop suddenly, and the lowest pressure is about 0.205MPa. The fluid flow state after the leak is similar to that of the second working condition. At 0.02s after the leak, the back pressure in the pipe rises, the flow velocity slows down, and the local vortex at the tee pipe increases significantly. In the 0.13s transient simulation, that is, 0.03s after the leakage occurs, the upstream two inlet branch fluids accelerate to the three-way junction under the action of the pressure difference force, where the two fluids meet, and the fluid is compressed to produce greater pressure energy. The pressure rises to about 0.33MPa. As the leakage progresses, the pressure in the pipe gradually stabilizes. Compared with the initial state, the pressure in the branch pipe where the leakage point is stabilized is slightly lower than the pressure value in the initial state.

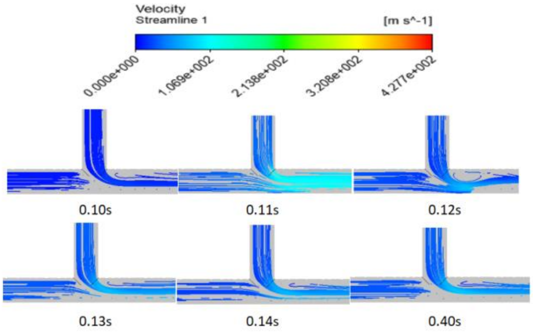

Figure 4.7 Transient speed change

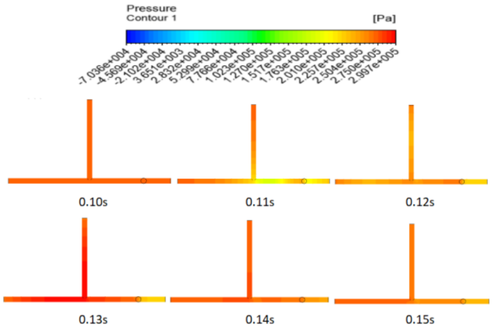

Figure 4.8 Transient pressure field change

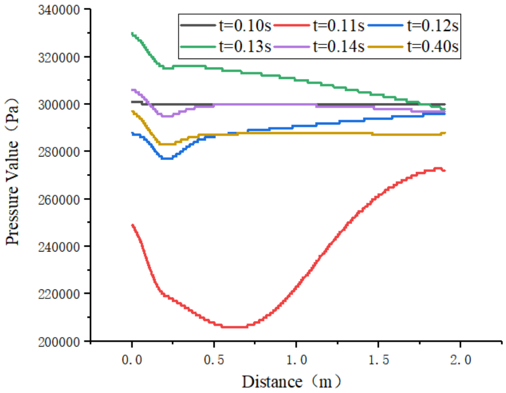

Figure 4.9 The pressure change diagram of the center line of the leaking branch pipe

5.4. Flow Field Analysis of the Fourth Leakage Condition

In the fourth leakage condition, the vertical pipe is set as the inlet and the two horizontal branch pipes are set as the outlet. Since the pipeline flow field is symmetrically distributed, only one horizontal outlet branch pipe leakage situation needs to be considered. In the initial state, the vertical inlet fluid impacts the bottom of the pipe, causing a wide range of flow separation phenomena. When the downstream pipeline leaks, the upstream and downstream fluids of the leakage port will flow out of the pipeline under the action of a huge pressure difference, and the pressure in the outlet branch pipe section will drop rapidly. , The lowest point can reach about 0.21MPa. Since the other outlet branch pipe did not leak, the fluid pressure in the pipe was much higher than that at the leak port, causing the fluid in the pipe section to flow back under the action of the pressure difference, the flow separation phenomenon disappeared, and the vertical inlet fluid merged and flowed toward the leak port. In the 0.12s of the transient simulation, the back pressure of the leaking pipe section increases and the flow velocity slows down, which leads to an increase in the range of the local vortex. In the 0.13s of the transient simulation, the fluid compression at the junction causes the pressure energy to increase to about 0.33MPa. Subsequently, the pressure fluctuation gradually decreased, and the pressure in the pipe gradually stabilized. After stabilization, the pressure in the branch pipe where the leakage point was located was slightly lower than the pressure value in the initial state.

5.5. Flow Field Analysis of the Fifth Leakage Condition

The fifth leakage condition sets two horizontal pipes as pressure inlets and vertical pipes as pressure outlets. In the initial condition, the fluids from the two inlet branch pipes merge at the three-way pipe and flow into the vertical outlet. However, due to the small pressure difference between the inlet and outlet, the fluid flow rate in the pipe is low. When the leakage occurs at the beginning, the entrainment effect is strengthened, and the fluid in the vertical branch pipe flows out of the pipe quickly, causing the pressure in the pipe section to decrease, and the lowest point is about 0.15MPa. In the first 0.12s of the transient simulation, the back pressure of the leaking pipe section increased, and the fluid flow rate in the pipe slowed down greatly; at the 0.13s, the fluid in the two inlet straight pipes accelerated to the junction of the pipes, and impacted each other here under the action of inertial force, and the gas was compressed , The kinetic energy is converted into pressure energy, so that the pressure in the pipe rises to about 0.33MPa, and then the confluence flows to the leakage port. The pressure of the branch pipe where the leakage point is located after stabilization is slightly lower than the initial pressure value in the pipe.

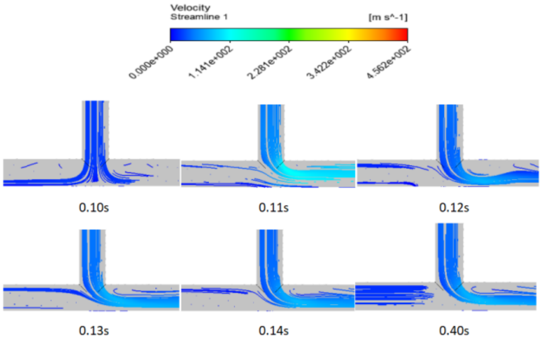

Figure 4.10 Transient speed change

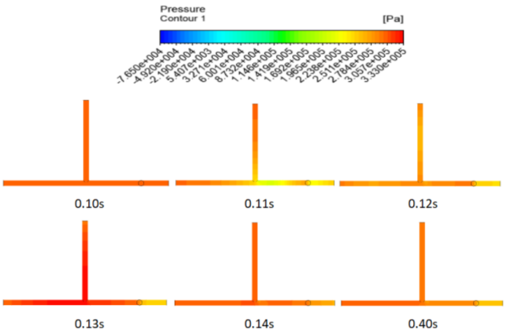

Figure 4.11 Transient pressure field change

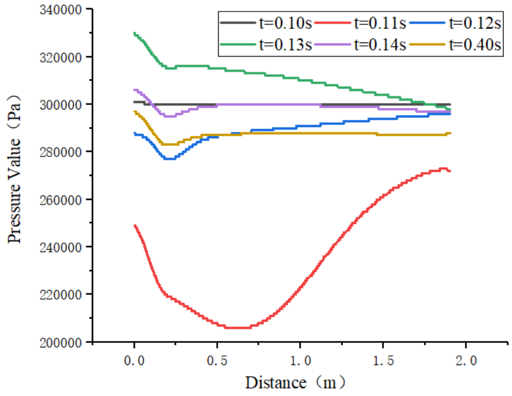

Figure 4.12 The pressure change diagram of the center line of the leaking branch pipe

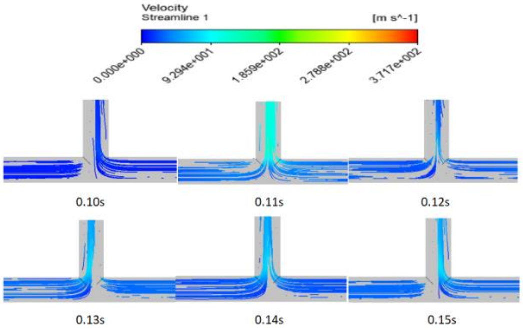

Figure 4.13 Transient speed change

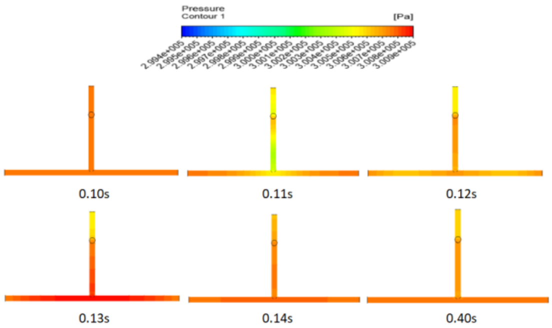

Figure 4.14 Transient pressure field change diagram

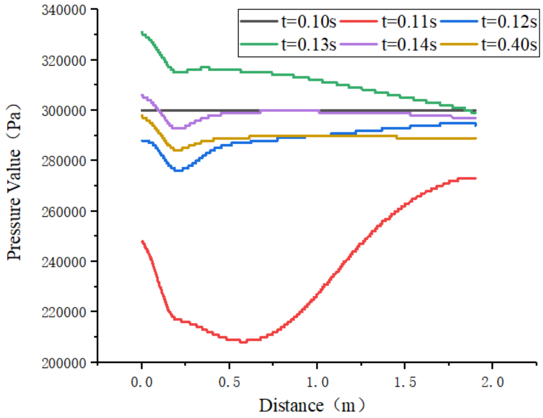

Figure 4.15 The pressure change diagram of the center line of the leaking branch pipe

6. Analysis of pressure fluctuation at origin of T-shaped pipeline

Take the centroid of the T-shaped three-way pipe to analyze the trend of the pressure of the three-way pipe with the leakage time, as shown in Figure 5.1 and Table 3. At the moment of leakage, that is, at the 0.11s of transient calculation, the pressure of the five leaking conditions all dropped to the lowest value, distributed between 240KPa and 247KPa; then the pressure rose, and the pressure in the pipe reached the peak value at about 0.13s, and the pressure distribution was 329KPa- Between 334KPa; afterwards, the oscillation amplitude gradually decreases, and the pressure fluctuation in the 0.25s after the leakage is almost zero, and the stable pressure is between 296KPa-300KPa. From the analysis of the peak changes of the five working conditions, the range is between 87KPa-91KPa, the range 3 and 4 are the largest, both are 91KPa, and the range 5 is the smallest, 87KPa. From the overall pressure fluctuation trend, the pressure fluctuation trend of the five leakage conditions is almost the same. After a large fluctuation in the early stage, it gradually stabilizes, and the stabilized pressure is slightly lower than the pressure without leakage.

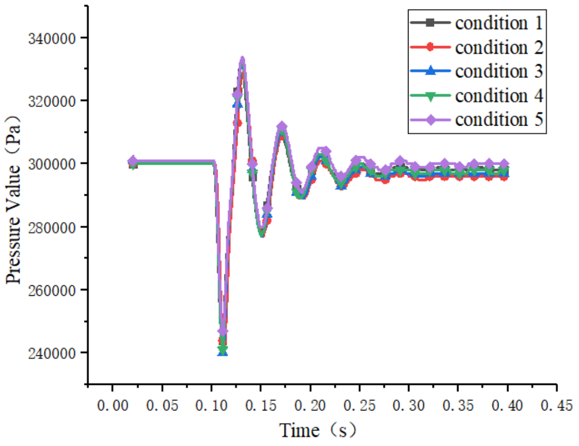

Figure 5.1 Origin pressure change

Table 3 Origin pressure extreme value

Pressure	Working condition 1	Working condition 2	Working condition 3	Working condition 4	Working condition 5
Lowest pressure (KPa)	244	241	240	241	247
Maximum pressure (KPa)	332	329	331	332	334
discrepancy (KPa)	88	88	91	91	87

7. Model validation

In order to determine the accuracy of the above-mentioned research content, the leakage volume under the steady state of working condition 2 is selected, and the leakage mass flow of the pipeline operating pressure of 0.30MPa, 0.35MPa, 0.40MPa, 0.45MPa, and 0.50MPa is theoretically verified. In the simulation conditions of this article, the operating pressure inside the pipe is set to 0.3MPa, the outside of the pipe is an atmospheric environment, and the pressure at the leakage port is set to standard atmospheric pressure. The pipeline gas leakage process can be expressed by equation (4) [10].

$$P_1^{\frac{n+1}{n}} - P_2^{\frac{n+1}{n}} = \frac{16(n+1)Q^2}{n\pi^2 D^4} P_1^{\frac{1-n}{n}} RT\left(\frac{\lambda L}{2D} + \frac{1}{n}\ln\frac{P_1}{P_2}\right) \tag{4}$$

The calculation of pipeline leakage can be expressed by formula (5):

$$Q = 0.25\mu\pi \mathrm{d}^2 \frac{P_2}{\sqrt{RT_2}} \sqrt{\frac{2k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}}} \tag{5}$$

In the formula, λis the friction resistance coefficient, which is calculated by the formula provided by the Urban Gas Design Code; D is the pipe diameter (m); Q is the leakage flow rate (kg/s);μis the flow coefficient, with a value of 0.98; d is the leakage port Diameter (m); R is the gas constant (287.1 J/kg·k); T_2 is the gas temperature in the tube (K); k is the gas adiabatic coefficient, with a value of 1.4. Synthesize the above-mentioned gas pipeline leakage model, use MATLAB to compile the corresponding program, and calculate the P_2 pressure value and Q pipeline leakage value by simultaneous two-type iterative calculation.

The software calculation value and the theoretical calculation value statistics list, as shown in Table 2. The results show that the maximum error between the simulation value and the theoretical calculation value is 13.50%, and the minimum error is 2.37%. The reason for the error is related to the mesh quality and the neglect of wall surface roughness in the model setting. It can be seen that the results of CFD simulation are related to The theoretical calculation results are in good agreement, and the calculation model established in this research has good simulation accuracy.

Table 2 Mass flow verification

Operating pressure value	Calculated	Theoretical value	Error
0.30Mpa	24.46kg/s	21.55kg/s	13.50%
0.35Mpa	27.87kg/s	25.14kg/s	10.86%
0.40Mpa	30.92kg/s	28.73kg/s	7.62%
0.45Mpa	33.97kg/s	32.32kg/s	5.11%
0.50Mpa	36.77kg/s	35.92kg/s	2.37%

8. Conclusion

According to the four types of import and export combinations in the gas pipeline network, five typical pipeline leakage models are established, and the FLUENT software is used to simulate and analyze the flow of the pipeline under sudden leakage. The conclusions are summarized in the following three points:

1. According to the leakage model established in this accident, after a large hole leakage occurred in the urban gas pipe network with an operating pressure of 0.3Mpa, the pressure of the tee pipe under the five working conditions fluctuates continuously, and the upper and lower peaks vary greatly, and the extreme difference is About 0.09Mpa, the fluctuation is basically stable after 0.25 seconds, and the pressure in the branch pipe where the leakage point is located is lower than the initial pressure value in the pipe after stabilization.

2. The change of fluid flow state is mainly determined by the pressure difference force. During the leakage process, the unsteady fluid flow intensifies, and the pressure pulsation of the pipeline will produce greater structural vibration, which can be used as one of the leakage signals for detection.

3. By analyzing the combination of four inlet and outlet pipelines and five leakage states, it can be seen that when leakage occurs, the pressure in the pipe fluctuates significantly, and the three-way pipe can receive a more obvious leakage signal, and the conditions of working

condition 1 and working condition 5 The flow field has similar changing trends, and the changing trends of working conditions 2, 3, and 4 are similar. The analysis of the changes in the flow field of the three-way pipe during leakage can provide theoretical guidance for the development of leakage detection devices.

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