Study on the influence of elbow with different curvature radii on pipeline leak location

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Abstract
Experimental and numerical methods are used to locate the pipeline leakage in the present work. The weak compressibility of the fluid is taken into account when simulating the propagation of negative pressure wave (NPW) in the pipeline. The NPW attenuation coefficient is used to describe the influences of curvature radius on location accuracy. The results indicate that when the curvature radius is small, the location accuracy of pipeline leakage is low. When the radius of curvature increases or the inlet pressure increases, the accuracy of pipeline leak location is improved. Besides, with the change of inlet pressure, pressure, and velocity distributions in the elbow with different curvature radii are investigated. When the curvature radius of the elbow is three to four times of pipe diameter, the measurement accuracy of leakage location is the best. When the inlet pressure of the pipeline is 0.7 MPa, the sensitivity of the pipeline detection is the highest. The cavitation corrosion at the elbow is the most obvious. Therefore, the elbow is the area where pipeline leakage occurs most frequently.

Keywords
Elbow, leak location, negative pressure wave, attenuation coefficient

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Introduction
The characteristic which is released consciously from the pipeline is called leakage. Pipeline leak is often caused by many factors, including sudden change of pipeline pressure, pipeline corrosion, foreign body in the pipeline, material defects, and so on. In most cases, the occurrence of a leak may result in some harmful consequences or even serious problems. Therefore, rapid detection, accurate location, and emergency maintenance of leaks are significant to energy saving and environmental protection.

When the fluid flows through a complex pipeline elbow, the pressure in the elbow will change significantly due to the sudden change of flow direction. This pressure feature will not only reduce the service life but also influence the sensitivity and measurement accuracy of elbow leak detection. Some variables in pipeline leak detection are not easy to measure in practice. Therefore, numerical simulation has been widely used in studying the flow characteristics and mechanisms in the elbow. Ming and Zhao simulated the internal flows of the three links. The results showed that the formation of three links in the vortex can be well observed by choosing the LES model. De Vasconcellos Araújo et al. have adapted CFD technology to simulate the location of pipeline leakage in the complicated case and the effect on pipeline internal flow. The...
pressure and velocity distributions, as well as the flow chart, were analyzed. The results demonstrated that the pressure fluctuation which caused by the leak in the main pipe is much larger than that caused by the leak in the branch pipe. The more leak holes there are, the more difficult it is to locate its position. Ben-Mansour et al. simulated the flow in the same position of different sizes of leak holes under steady and transient conditions. The numerical results showed that there will be no large fluctuation in the pressure signal if the leak rate is small, but the leak will increase the amplitude and frequency of the signal. Moreover, the leak will greatly influence the pressure gradient. The pipeline pressure and leak size also have a great influence on the leak flow rate. Liu et al. used CFD technology to analyze the pressure pulsation. It is proved that CFD is an effective way to simulate the acoustic leak detection and location method.

A lot of efforts have been made on how to better monitor the pipeline leak and continued. Before and after the leak, Kam studied the steady response of the system. The results show that the use of higher flow gas fraction and lower back pressure would better enlarge the leakage in the oilfield operation. Molina-Espinosa et al. simulated the pipeline flow by using the finite differences technique. They proposed a mechanical model to study the influence of the convection term on the short pipeline leakage location pressure prediction in momentum equation. Odumabo et al. and Yan et al. used CFD and experimental tools to study the hindrance of underground gas pipeline leakage to gas flow in low permeability sandstone and the diffusion of methane in soil. Ebrahimi-Moghadam et al. built a two-dimensional, turbulent, and compressible gas flow model. The correlation method is used to estimate the amount of natural gas leakage from overground and underground urban gas pipelines. The results showed that this model presented high accuracy correlations. This is developing more accurate and more powerful computing tools. One step is taken in predicting the influence of potential accidents and consequences of hazardous materials leakage.

Across the pipeline industry, there is growing interest in improving the capabilities of leak detection systems. The use of internal methods based on pipeline pressure measurements, including the negative pressure wave (NPW) method, not only allows faster detection, but also allows the location of leaks. Ostapkoicz provides an algorithm program to solve the problem of leakage detection of infusion pipeline. This scheme is suitable for NPW and gradient method. The results confirmed that these algorithms achieved high efficiency in single leak diagnosis. Bai et al. developed a leak detection system. It has leak detection and location modules. Sequential probability ratio test, NPW method, and pressure gradient method were used. The test and comparison showed that the leak detection system has good sensitivity and accuracy. A reference is provided for further research on leak detection. Jia et al. considered the NPW energy attenuation. The performance of the developed fiber Bragg grating hoop strain sensors was analyzed. The results show that setting mounts of sensors can be increased by more than 30% of the minimum detectable leak rate. The fiber Bragg grating hoop strain sensor with higher development sensitivity is the most effective way to improve the overall performance of the leak detection system. Anwar et al. compared localization accuracy with NPW and pressure point analysis, including detection and localization techniques. The results show that the ISTS method can be used to detect and locate multiple anomalies in different locations at the same or different times.

However, the current research target mainly focuses on the straight pipe, and the influences of the elbow on leakage include the sensitivity and accuracy of pipe leak detection have not been well studied and solved. Besides, the internal flow features include pressure, velocity and NPW in the elbow are worth studying. Therefore, in this work, the experimental and numerical methods are applied to investigate the influence of elbows with different curvature radii on pipeline leak location. The commercial software Fluent is used to simulate the flow of the elbow, the internal flow is observed and its coefficient is analyzed.

### Theory and methodology

The variation of the curvature radius of the elbow under different inlet pressures with NPW attenuation coefficient and location accuracy was obtained through the experiment. It was verified by numerical simulation in this work. Besides, the pressure distribution and velocity distribution of the internal flow in the elbow were analyzed by numerical simulation.

#### Compressible Navier–Stokes equations

Once the pipeline leaks, the fluid leakage at the leak point leads to a decrease in density. The pressure at the pipeline leakage decreases sharply. The pressure drop near the leak point causes the nearby liquid to be filled towards the leakage area, resulting in a reduction of surrounding density and pressure. The signal of the pressure reduction begins to be transmitted to the pipes on both sides, which is called NPW. Since the fluid itself contains small bubbles, the density of the fluid does not tend to remain constant after a pipeline leak occurs. The transmission of the NPW depends on this weakly compressible characteristic.

For unstable compressible flow, the continuity equation is as follows:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]  

(1)

where \( \rho \) is the density of the fluid, \( \mathbf{v} \) is the fluid vector, and \( t \) is the time.

The momentum equation is as follows:

\[ \frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \mathbf{\tau} \]  

(2)

where \( p \) denotes the pressure, \( \mathbf{\tau} \) is viscous stress tensor.

For moderate Mach numbers, the density, pressure, and length of the physical domain are treated dimensionless. All other references are calculated based on these dimensional relationships. Therefore, the fluid and sound share the same reference velocity. As the Mach number approaches zero and the eigenvalues of these quantities differ greatly, this scaling becomes inappropriate. Therefore, a separate reference velocity is introduced in this work. The basic dimensionless variables are as follows:

\[ \rho = \frac{\rho}{\rho_{ref}} \]  

(3)

\[ \mathbf{v} = \frac{\mathbf{v}}{v_{ref}} \]  

(4)

\[ x = \frac{x}{x_{ref}} \]  

(5)

\[ \bar{p} = \frac{p}{p_{ref}} \]  

(6)

where \( \rho, \mathbf{v}, x, \bar{p} \) represent dimensionless density, velocity, spatial coordinate, and pressure, respectively. The subscript \( \text{ref} \) means reference value. Therefore, \( \rho_{ref}, v_{ref}, x_{ref}, p_{ref} \) represent the parameter values of density, velocity, spatial coordinate, and pressure, respectively.

The dimensionless Mach number \( \mathcal{M} \) is

\[ \mathcal{M} = \frac{v_{ref}}{\sqrt{p_{ref}/\rho_{ref}}} \]  

(7)

The dimensionless time \( \bar{t} \) is

\[ \bar{t} = \frac{t}{(x_{ref}/v_{ref})} \]  

(8)

The compressible Navier–Stokes equations should be written as

\[ \frac{\partial \bar{p}}{\partial \bar{t}} + \nabla \cdot (\bar{p} \bar{v}) = 0 \]  

(9)

\[ \frac{\partial}{\partial \bar{t}} (\bar{p} \bar{v}) + \nabla \cdot (\bar{p} \bar{v} \bar{v}) + \frac{1}{\mathcal{M}^2} \nabla \bar{p} = \frac{1}{\Re} \nabla \cdot \mathbf{\tau} \]  

(10)

where \( \Re \) is dimensionless Reynolds number.

**Experimental setup**

As shown in Figure 1, the experimental scheme consists of the reservoir, pump, pneumatic valve, electromagnetic flow meter, digital pressure sensor, and temperature sensor. Water pumps from the reservoir into the pipe then passes through the pneumatic valve and the test section and finally travels back to the reservoir. The electromagnetic flowmeters are installed upstream and downstream of the test section. The location of the digital pressure sensor is consistent with that of the monitoring points in Figure 3. The test section is shown in Figure 2, including the pressure sensor and pipeline leak. The nominal diameter \( D \) of the experimental pipeline is 150 mm, the measurement precision of the high-precision digital pressure sensor is 0.1%, and the measurement accuracy of the flow meter is 0.5%. The experiment was repeated five times in each condition, and the average value was calculated to reduce random error.

**Numerical method and boundary conditions**

To collect the data required for numerical simulation, some monitoring points are added to the experimental system. The distribution of them in the pipeline is shown in Figure 3. The nominal pipe diameter is
0.15 m, length of the straight pipe is 23 m. The distance from monitoring point 1 to the pipeline inlet is 2 m, and the distance to the leak point is 12 m. Monitoring point 2 to the leak point is 2 m. Monitoring point 3 and monitoring point 4 are set at the inlet and outlet pipe elbow. The distance from monitoring point 4 to monitoring point 5 is 1.5 m. In addition, \( d \) is the pipe diameter, and \( R \) is the curvature radius of elbow. The calculation domain of pipe elbow in numerical simulation is shown in Figure 4. To improve the efficiency of the calculation, a hybrid grid combining the structured grid and the unstructured grid is used for calculation.

The pressure drop in the elbow is used to study the grid independence. Table 1 shows three grids with different nodes, and the pressure drops in various elbows. Among them, \( P_3 \) and \( P_4 \) represent the pressure collected at elbow monitoring points 3 and 4, and \( \Delta P_1 \) is the pressure drop collected from monitoring point 3 to monitoring point 4. The results show that when the grid number exceeds 4 million, the pressure drop presents a slight difference with the increase of grid nodes.

Therefore, the accuracy and efficiency of the model is improved by using a grid with 4 million nodes for simulation. Besides, the mesh around the hole is locally refined, which improves the accuracy of the simulation. The \( k-\varepsilon \) turbulence model is used to simulate turbulent flow. The second order upwind discrete equation is selected to solve the convection term. The boundary conditions of pipeline inlet and outlet is inlet and outlet pressure. Firstly, the boundary condition of the leak is selected as the pipeline with stable inner wall pressure after a short time. And then the outlet pressure will be adopted as the leak boundary condition.

### Results and discussion

#### NPW attenuation coefficient

Because of the pressure difference, the fluid outflows from the leak hole when the leakage occurs. And it leads to pressure drop near the leakage area, as well as the pressure leak and downstream transmission. This transmission can be called NPW propagation due to the pressure generated in the hydraulic leak. The propagation of NPW in the fluid can be regarded as the propagation of sound waves in the fluid. The location principle is shown in Figure 5, and the expression is as follows:

\[
X = \frac{1}{2u}\left[ s(u - v) + \Delta t(u^2 - v^2) \right]
\]

where \( X \) is the distance from the leak point to monitoring point 1, m; \( u \) is the speed of NPW, m/s; \( s \) is the distance between monitoring point 1 and monitoring point 2, m; \( t_1 \) and \( t_2 \) are the time for the NPW to propagate from the leak point to the monitoring point 1 and the monitoring point 2 respectively, s; \( v \) is the flow velocity, m/s.

The propagation of NPW in the pipeline can be regarded as a form of energy transmission. With the increase of propagation distance, the NPW decays...
gradually. As the NPW passes through the elbow, the attenuation becomes more obvious. It affects the pipeline leak detection sensitivity significantly, thus the final location accuracy is reduced. It is difficult to calculate the energy loss when the fluid flows through the elbow in practical engineering applications. Therefore, the attenuation coefficient is meaningful to describe the energy loss. To study the propagation of NPW, monitoring point 1 and monitoring point 2 (shown in Figure 3) are selected. The calculation of the NPW attenuation coefficient is as follows:

\[ \alpha = \frac{f Q}{u A r D} \]  

where \( f \) is the hydraulic friction coefficient; \( Q \) is the mass flow rate, kg/s; \( u \) is the speed of NPW, which is obtained by measurement, not a fixed value in this work, and is a dependent variable of the current state of the fluid in the measurement process, m/s; \( A \) is the cross-sectional area of the pipe, m\(^2\); \( \rho \) is the fluid density, kg/m\(^3\); \( D \) is the nominal diameter of the pipe, m; \( \alpha \) is the NPW attenuation coefficient.

Figure 6 shows that under different inlet pressure conditions, the attenuation coefficient varies with the change of curvature radius of the elbow. As can be seen from Figure 6, when the inlet pressure is constant, the attenuation coefficient decreases and tends to be flat with the increase of the curvature radius of the elbow. When the curvature radius of the pipe elbow is small, the pressure drop after the fluid flows through the elbow is large. At this time, because the NPW attenuates quickly, when the NPW flows through the pipe elbow, the pressure change caused by the NPW will become very small. It will affect the detection of pipeline leakage and reduce the accuracy of pipeline leak location. This situation has a particularly significant impact on the detection of a small leak in long-distance pipeline transportation. When the curvature radius of the elbow is constant, the NPW attenuation coefficient decreases with the increase of the pipeline inlet pressure. However, when the inlet pressure of the pipeline reaches a certain degree, the influence of the inlet pressure on the NPW attenuation coefficient will be weakened. Figure 7 can prove this point regarding the location accuracy of pipeline leaks.

Equation (11) is used to predict the distance between the leak point and the monitoring point 1. The actual distance between the leak point and the monitoring point 1 is known in the experimental structure. The accuracy of pipeline leak location can be obtained by comparing the prediction value of equation (11) with the actual location of the leak point in the experiment.
Figure 7 shows that the pipeline leak location accuracy changes with the change of the elbow curvature radius. As can be seen from Figure 7, under the condition that the inlet pressure of the pipeline is constant, the smaller the elbow curvature radius, the worse the pipeline leak location accuracy. With the increase of the curvature radius of the elbow, the location accuracy of leakage location increases. When the curvature radius of elbow is large to 3–4d, the influence of the elbow curvature radius on leak location accuracy will be very small.

When the curvature radius of the elbow is constant, the accuracy of leak location will be improved with the increase of inlet pressure, especially for the pipe with a small elbow radius. However, when the pipeline pressure reaches 1.5 MPa, the accuracy of pipeline leak location no longer improves with the increase of pipeline pressure.

**Pressure distribution**

The pressure distribution in the pipe elbow is shown in Figures 8 and 9. The pressure distribution in the pipe is relatively uniform until the fluid passes through the elbow. When the fluid passes through the pipe elbow, the flow direction changes suddenly under the action of centrifugal force. There are low-pressure and high-pressure areas inside and outside of the pipeline. When the fluid flows through the elbow into the straight pipe, the distribution of pressure in the pipeline becomes uniform again. The pressure on the inside of the pipe decreases and then increases. The pressure on the outside of the pipe increases and then decreases. The pressure difference between the inner side and the outer side of the pipe can reach a maximum value. With the increase of curvature radius of elbow, the centrifugal force becomes smaller. Therefore, the pressure drop between inside and outside of pipe becomes smaller. After the pipeline leak, the internal pressure of the pipe is a huge fluctuation instantly. The internal pressure of the pipe recovered smoothly after a short period. However, compared with that before the leak, the overall pressure decreases in the pipeline. The pressure drop is decreased inside and outside the pipeline elbow.

The pipeline leak detection sensitivity is related to the pressure drop degree after the leak. The pressure drop is affected by many factors, such as the size of the pipeline leak, the location of the leakage, the curvature radius of the elbow, the size of the inlet, and so on. The elbow influences the sensitivity of pipeline leak detection. When the fluid flows through the elbow, the pressure loss is much larger than that of the straight pipe through the same distance.

Six elbows with different curvature radii are selected for simulation to investigate the pressure drop in the elbow. As demonstrated in Figure 10, the pressure data collected from monitoring point 3, monitoring point 4, and monitoring point 5 (shown in Figure 3) are selected. \( \Delta P_1 \) is the pressure drop collected from monitoring point 3 to monitoring point 4. \( S_1 \) is the distance from monitoring point 3 to monitoring point 4 along the pipeline centerline, that is, the equivalent length of the elbow. The pipe elbow is converted into the equivalent length of the straight pipe, which is called the equivalent length of the elbow. \( \Delta P_2 \) is the pressure drop...
collected from monitoring point 3 to monitoring point 5, and $S_2$ is the distance from monitoring point 3 to monitoring point 5 along the pipeline centerline.

As shown in Figure 10, the pressure drop between monitoring point 3 and monitoring point 4 increases as the curvature radius increases. The pressure drop per unit distance from monitoring point 3 to monitoring point 4 along the pipeline centerline also presents a similar trend. This is because of the larger curvature radius, resulting in a greater pressure drop of the elbow. The
influence of the elbow on the pressure drops extends to the back of the elbow. Therefore, monitoring point 5 is set at 1.5 m after monitoring point 4. It is used to study the pressure change after the fluid passes through the elbow for a certain distance. For the straight pipes with the same distance but different equivalent lengths of elbows, the pressure drop from monitoring point 3 to monitoring point 5 decreases and then increases as the curvature radius increases. The results show that when the curvature radius in the range of 1–4d, the pressure drop after the fluid flows through the elbow of 4d from monitor point 3 to monitor point 5 is less than that after the fluid flows through the elbow of 1d. With the increase of the curvature radius, the elbow equivalent length increases furtherly. Therefore, when the elbow curvature radius is greater than 4d, pressure drop from monitoring point 3 to monitoring point 5 increases. Therefore, the curvature radius of the elbow is best selected as 3–4d. The pressure drop caused by elbow can be reduced, and the sensitivity of pipeline leak detection can be improved.

To investigate the pressure loss in the elbow, the influence of four different pipe inlet pressures on elbow pressure drop is described in Figure 11. Under the condition of a certain elbow curvature radius, the pressure drop of the elbow slowly decreases and then gradually stabilizes with the increase of the inlet pressure. Based on the analysis above, when the pipe inlet pressure is smaller (less than 0.7 MPa), the pressure lost by the fluid flowing through the elbow is large, which influences the pipeline leak detection sensitivity greatly. When the pipe inlet pressure is larger (more than 0.7 MPa), the elbow pressure drop no longer decreases with the increase of the pipeline inlet pressure. Therefore, to minimize pressure drop of the elbow and improve the pipeline leak detection sensitivity, it is better to select 0.7 MPa for pipeline inlet pressure. However, the selection of pipeline inlet pressure should not be too large. It is easy to rupture the pipeline when the pipeline inlet pressure is too large.

Figure 12 shows the pressure distribution in the elbow with a curvature radius of 3d at different instants after the leak. It can be seen that when the leak occurs, the fluid flows unsteadily in the pipeline. This is because the external pressure of the pipeline is less than the internal pressure of the fluid, which makes the leak hole flow from the laminar to turbulence. At the moment of leakage, it takes some time for the NPW to propagate in the pipeline. When $T = 0.001$ s, the NPW does not arrive near the elbow, and there is no obvious change in elbow pressure. With the increase of the leak time, after the NPW propagates along with the pipeline transmission for 0.015 s (i.e. at 2.015 s), internal pressure near the elbow will suddenly drop, then rise, and then suddenly drop again. This series of pressure fluctuations are all completed in a short period. With the further increase of leak time, the pressure wave flowing near the pipe elbow gradually stabilizes. After 2 s (i.e. at 4 s), the pressure wave near the pipe elbow is basically within the normal fluctuation range.

Figure 13 shows the transient pressure variation in three different positions of pipeline elbow. It can be seen that due to the sudden change of the flow direction, the pressure near the middle of the pipe elbow is lower than the pressure at the inlet and outlet of the elbow. However, the pressure at each position of the elbow changes similarly over time.
Velocity distribution

Figures 14 and 15 describe the velocity distribution in the Z direction of the pipe elbow before and after the leak. It can be seen that the distributions of velocity and pressure are exactly the opposite. There is a high-velocity area on the inner side of the pipe elbow, and a low-velocity area located on the outer side. The inner velocity first increases and then decreases, whereas the outer velocity shows an opposite change trend. The reason is that when the fluid flows through the elbow, the flow direction will suddenly change. Under the action of centrifugal force, the fluid will squeeze the outer wall surface of the elbow and will form a traction effect on the inner wall surface of the elbow. As a result, the pressure in the pipeline gradually increases along the direction of the centrifugal force. According to Bernoulli’s principle, the total energy per unit weight of fluid at each point in the same pipeline is constant. That is, if some energy increases along the pipeline, other energy must decrease. Therefore, under the premise that the gravitational potential energy remains unchanged, the increase in kinetic energy of pressure potential energy will decrease correspondingly, and so will the decrease in kinetic energy of pressure potential energy.

Kinetic energy can be transformed into pressure potential energy on the outer side of the elbow. Therefore, the pressure of the fluid acts on this area is the largest, and the impact force of fluid on this area is also the largest. The impact force easily causes the corrosion on the inner side of the pipeline. The material of the pipe wall is exposed to the corrosive fluid. It accelerates the chemical reaction and electrochemical reaction between the pipe and the fluid, and aggravates impact corrosion. It is also one of the main reasons for perforation and cracking on the outside of the pipe elbow. Meanwhile, near the inner wall of the elbow, the pressure potential is greatly transformed into kinetic energy, so that the pressure in this area drops suddenly. When the pressure drops below the saturated vapor pressure in this area, cavitation occurs. When the fluid passes through the pipe elbow, the sharp change of flow direction leads to the formation of the vortex. The vortex interacts with the bubbles and exerts an obvious

Figure 12. Pressure contour of the elbow of 3d after the leak.

Figure 13. Pressure with time at different positions.

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effect on the pipe wall. Besides, when the bubbles collapse, a shock wave will be generated. The repeated shock pressure under the combined action of the shock wave and the micro-jet cause intense damage to the pipe wall and form cavitation corrosion. As the curvature radius of the elbow increases, the flow velocity in the pipe elbow decreases. The vortex at the pipe elbow is slowly weakened, and the cavitation corrosion is weakened correspondingly. After the pipeline leaks, the flow velocity in the pipeline increases, making the

Figure 14. Velocity contour of pipe elbow before the leak.

Figure 15. Velocity contour of the pipe elbow after the leak.
vortex at the elbow more intense. The impact force of the bubbles carried by the vortex on the pipe wall becomes greater, which further intensifies the cavitating corrosion. Therefore, it can be known from the above analysis that the pipe elbow not only affects the sensitivity of pipeline leak detection but also is the main area where pipeline leak occurs.

Conclusion

The experimental and numerical methods are used in this work to research the internal flow characteristics in the elbow, and the influence of the elbow on leak location accuracy. There some main conclusions can be obtained:

1. The NPW can be used to detect the location accuracy of the leakage in the elbow. After 2 s of the leak, the NPW is stable. When the curvature radius of the elbow is small, the rate of decay is large, and the location accuracy decreases. With the increase of inlet pressure, the NPW attenuation coefficient decreases and the location accuracy is improved.

2. Under the condition that the inlet pressure of the pipeline is constant, when the curvature radius of the elbow is three to four times of the pipe diameter, the location accuracy of the leakage is obviously improved.

3. When the fluid flows through the same elbow, the pressure loss is the smallest and the pressure drop of the elbow is the smallest, which will improve the pipeline leak detection sensitivity. It is best to select 0.7 MPa for pipeline inlet pressure.

4. When the fluid passes through the elbow, the flow velocity increases with the decrease of the curvature radius of the pipe elbow. At this time, the phenomenon of cavitating corrosion is more obvious. Therefore, the elbow is the area where the pipeline leaks most frequently.

This study guides the selection of elbows for pipeline transportation projects and also guides the research of pipeline leak location accuracy.

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References

1. Xu J, Li D, Guo J, et al. Investigations of phase inversion and frictional pressure gradients in upward and downward oil–water flow in vertical pipes. Int J Multiph Flow 2010; 36: 930–939.
2. Ming T and Zhao J. Large-eddy simulation of thermal fatigue in a mixing tee. Int J Heat Fluid Flow 2012; 37: 93–108.
3. De Vasconcellos Araújo M, de Luna FDT, Barbosa ES, et al. Numerical study of oil flow in tee junction with leaks. Adv Pet Explor Dev 2013; 6: 1–11.
4. Ben-Mansour R, Habib MA, Khalifa A, et al. Computational fluid dynamic simulation of small leaks in water pipelines for direct leak pressure transduction. Comput Fluids 2012; 57: 110–123.
5. Liu C, Li Y, Meng L, et al. Computational fluid dynamic simulation of pressure perturbations generation for gas pipelines leakage. Comput Fluids 2015; 119: 213–223.
6. Kam SI. Mechanistic modeling of pipeline leak detection at fixed inlet rate. J Pet Sci Eng 2010; 70: 145–156.
7. Molina-Espinosa L, Cazarez-Candia O and Verde-Rodarte C. Modeling of incompressible flow in short pipes with leaks. J Petrol Sci Eng 2013; 109: 38–44.
8. Odumabo SM, Karpyn ZT and Ayala HLF. Investigation of gas flow hindrance due to fracturing fluid leakoff in low permeability sandstones. J Nat Gas Sci Eng 2014; 14: 1–12.
9. Yan Y, Dong X and Li J-M. Experimental study of methane diffusion in soil for an underground gas pipe leak. J Nat Gas Sci Eng 2015; 27; 82–89.
10. Ebrahimi-Moghadam A, Farzaneh-Gord M and Deymi-Dashtebayaz M. Correlations for estimating natural gas leakage from above-ground and buried urban distribution pipelines. J Nat Gas Sci Eng 2016; 34: 185–196.
11. Ostapkowicz P. Leak detection in liquid transmission pipelines using simplified pressure analysis techniques employing a minimum of standard and non-standard measuring devices. Eng Struct 2016; 113: 194–205.
12. Bai Y, Zhang T, Li Y, et al. A new leak detection method for subsea pipelines. Ships Offshore Struct 2017; 12: S144–S152.
13. Jia Z, Ren L, Li H, et al. Performance study of FBG hoop strain sensor for pipeline leak detection and localization. J Aerosp Eng 2018; 31: 04018050.
14. Anwar S, Sheltami T, Shakshuki E, et al. A framework for single and multiple anomalies localization in pipelines. J Amb Intel Hum Comp 2019; 10: 2563–2575.
15. Lin PF, Song PF, Zhu ZC, et al. Research on the rotor-stator interaction of centrifugal pump based on sinusoidal tubercle volute tongue. *J Appl Fluid Mech* 2021; 14: 589–600.

16. Munz CD, Roller SP, Klein R, et al. The extension of incompressible flow solvers to the weakly compressible regime. *Comput Fluids* 2003; 32: 173–196.

17. Yang Z, Fan S and Xiong T. Simulation and numerical calculation on pipeline leakage process. In: *Proceedings of the 2010 second international symposium on information engineering and electronic commerce (IEEC)*, Ternopil, Ukraine, 23–25 July 2010, pp.1–5. Piscataway, NJ: IEEE.

18. Ge C, Wang G and Ye H. Analysis of the smallest detectable leakage flow rate of negative pressure wave-based leak detection systems for liquid pipelines. *Comput Chem Eng* 2008; 32: 1669–1680.