Leakage monitoring research and design for natural gas pipelines based on dynamic pressure waves

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Abstract: Many types of gases, such as natural gas, hydrogen, and so on, are transported via pipelines using a chemical process, though leakages in these pipelines create waste and pose hazards and risks to industries, the environment and people. To monitor gas pipelines, a new leak detection and location method based on the amplitude attenuation model of dynamic pressure waves was designed and researched by experiments, compared with traditional method based on the propagation velocity and time differences as determined by the waveforms of the upstream and downstream signals. Both methods are achieved based on the propagation law of the dynamic pressure waves in the fluid flow. First, the fundamentals of the newly proposed method are clarified by considering the influence of gas flow on the waves. The experiments are then conducted in gas pipelines with 42 mm internal diameters. Finally, the results of the experiments are discussed and analyzed. The results indicate that all leakages can be detected by both methods but that the largest location error of the traditional method is -0.780%, whereas the largest location errors with respect to the new method are 0.054% with the experimental attenuation coefficients and 2.055% with the theoretical attenuation coefficients. It is further determined that the influence of the gas flow effects cannot be ignored by either method. Accordingly, the conclusions drawn suggest that the proposed methods can be applied to monitor gas pipelines.

Keywords: leakage monitoring; gas pipelines; dynamic pressure wave; gas flowing effect; experiments

25 1 Introduction

26 With the rapid development of the pipeline industry, chemical gases, such as natural gas, hydrogen,
27 etc., are being transported via pipelines, and thus, leakages in these pipelines occur occasionally that
28 pose hazards and risks to the environment and the people. Taking into account that natural gas
29 availability is not inexhaustible, its cost is extremely high. Therefore, to monitor pipelines, many
30 leak detection and location methods ^[1] have been developed. For example, Alkhaledi ^[2] used the fault
31 tree analysis to identify the source of leaking gas, and the results serve as a useful reference if any
32 similar gas leak incidents occur elsewhere. Elaoud ^[3] presented a technique using transient negative
33 pressure waves initiated by the sudden closure of a downstream shut-off valve. The presence of a
34 leak in a pipe partially reflects these pressure waves and allows for the location of the leak. Scott ^[4]
35 employed a method based on a real-time transient model that can detect small leaks, albeit it has the
36 disadvantage of being very expensive. Moreover, as the models employed are complex, they require
37 a trained user. Doothy ^[5] proposed a real-time pipeline leak detection method that incorporates
38 volume balancing to detect and locate small leaks. However, if small leaks occur, it takes
39 considerable time to detect them, and furthermore, Doothy's system is prone to false alarms during
40 transient states unless thresholds are adapted. Zhang ^[6] proposed a novel hybrid technique for leak
41 detection and location based on a real-time transient modeling method combined with a negative
42 pressure wave method. The results of the experiments indicated that Zhang's hybrid technique
43 successfully detects and locates gas pipeline leaks.

44 To describe the methods, the evaluation indexes are clarified as follows. (1) Sensitivity refers to the
45 smallest leakage rate that can be detected. (2) Location accuracy equals the absolute differential
46 value divided by the pipeline length, which equals the located leakage point minus the actual leakage
47 point. (3) False alarms are those alerts that occur when there is no leakage. (4) Missing alarms refer
48 to the failure of alarms to alert when a leakage does occur. (5) Detection time is the time the method
49 takes to detect and locate the leakage point. (6) Cost is the money spent for facilities and

50 maintenance charges. For each index, a score of 0 is awarded to the worst method, and a score of 5 is
51 awarded to the best method, i.e., the larger the score, the better the method.

52 According to the evaluation indexes, the usual methods identified above including the acoustic
53 method are presented in Table 1.

54 From among the presented methods, the acoustic method is found to be more promising. Lee ^[7]
55 established an oil and gas pipeline failure prediction system using long range ultrasonic transducers
56 (LRUT) and a Euclidean-support vector machine (E-SVM) classification approach. The results
57 indicate that the E-SVM approach is ideally suited for classifying data from pipelines. Yan ^[8]
58 proposed the gas leak detection technology of the spacecraft in orbit based on an acoustic sensor
59 array. The detection distance and direction of the array are verified by the experiments. The method
60 based on the dynamic pressure wave is one type of acoustic method that uses dynamic pressure
61 sensors, where the acoustic waves measured by the dynamic pressure sensors have a wide frequency
62 range of which the low frequency component can spread over a long distance. Thus, due to its
63 advantages, it has been researched increasingly more frequently.

64 The key aspect of a leak detection system based on an acoustic method is the ability to extract the
65 effective characteristics from the measured signals. Currently, the main filtering methods are based
66 on time domain and frequency domain analyses, though the blind source separation method has also
67 been studied. Yan ^[9] proposed an improved algorithm of median filtering based on extremum
68 detection, and the results indicate that the proposed algorithm is superior to traditional ones with
69 respect to noise removal and edge retention. Xu ^[10] proposed a de-noising algorithm via Wiener
70 filtering in the shearlet domain and found that the combination removes noises more effectively than
71 other methods. Hu ^[11] proposed a new signal extracting method that combines a wavelet de-noising
72 technique and the short-time Fourier transform method. The feasibility and accuracy of Hu's
73 proposed method are verified by numerical simulation and practical experiments. Mostafapour ^[12]
74 proposed a combination method of wavelet transform and a cross-time frequency spectrum to

75 process signals. The resulting locating error indicates high precision of the proposed algorithm. Lu^[13]
76 applied fast independent component analysis (FastICA) to measure non-Gaussian independent
77 components in blasting vibration signals as the approximation signals were separated, and the results
78 indicate that the approximation signal close to the source signal can be precisely separated using the
79 FastICA approach. Ni^[14] proposed the combination of a wavelet packet and information entropy and
80 the combination of empirical mode decomposition and information entropy. Under the condition of
81 high noises, the proposed method is applied better. Sun^[15] proposed a leak aperture recognition and
82 location method based on the root mean square entropy of a local mean deposition and Wigner-Ville
83 time-frequency analysis. The results indicate that the method can effectively identify different leak
84 apertures and that the leak location accuracy is better than that of other methods. Liu^[16] conducted
85 the time-frequency analysis of the acoustic leakage signal measured by dynamic pressure sensors
86 based on the Hilbert-Huang transform, and the results found that effective characteristics of dynamic
87 pressure waves can be extracted.

88 After the leakage characteristics are extracted, they are applied to locate the leak, a task for which the
89 time differences and velocities are important. Ye^[17] developed an analytical model to predict the
90 cross correlation function of leak signals in plastic water pipes, which can be used to calculate the
91 time difference and improve leak location accuracy. Brennan^[18] presented a new interpretation of the
92 process of cross-correlation for time delay estimation and found that time delay estimations and their
93 variances calculated using time and frequency domain methods are almost identical. Meng^[19]
94 established a formula using dynamic pressure waves to determine the locations of gas pipeline leaks.
95 Meng's formula can be modified based on the influences of temperature and pressure. Liu^[20]
96 established a generation model of dynamic pressure waves to extract precise time differences and
97 improve leak location accuracy.

98 Most of the extant studies have been conducted to improve the accuracy of velocity and time
99 differences according to which the method is called the traditional leak location method. A dynamic

100 pressure wave is generated, transmitted through fluid and acquired by sensors that are installed at
101 both ends of the pipeline. It is then processed to extract specific characteristics to determine whether
102 a leak has occurred and to calculate the time differences to locate the leak. Once leakage occurs, the
103 computer sends out alarms and locates the leakage if accurate velocity and synchronized timing
104 measurements can be achieved. However, it is difficult to confirm velocity due to different pressures
105 and temperatures. Thus, velocity calculation requires more pressure and temperature sensors,
106 especially for gas pipelines. Furthermore, if the method is applied to field or long distance pipelines,
107 the time difference calculation requires the data be well synchronized, as presented in Fig. 1. Fig. 1
108 indicates that the variation in reporting times from one data acquisition device (DAD) to the
109 computer can be quite large. Because the time-stamping is usually not performed at the level of the
110 DAD but rather at the centralized computer level, this procedure yields uncertainty regarding the age
111 of data that are collected in computer. This issue is also discussed by Magnis and Petit ^[21] as they
112 considered the importance of data synchronization with respect to loss detection. They noted that the
113 data should be carefully time-stamped with accurate and synchronized clocks, e.g., GPS or Rugby
114 clocks, though they are not readily available and are subject to jamming in many areas. Unfortunately,
115 these recommendations are far from optimal technical status observed in currently installed systems.
116 Petit ^[22] analyzed problems induced by the imprecise dating of measurements, especially the
117 mis-synchronization in oil and gas production. The results reveal that when signals with significant
118 time variations are monitored, the impact of the dating of measurements can be troublesome or even
119 worse than measurement noises. Accordingly, the above analyses suggest that the time difference
120 calculation is a problem in the application of the acoustic method. Based on this perspective, the
121 method without velocity and time differences can be considered to be more concise and easier. Thus,
122 Liu ^[23] proposed a method based on amplitude, for which the propagation law is researched. When a
123 leak location approach is conducted, the errors are large, i.e., greater than 1%, primarily because
124 when the propagation law is researched, the gas flowing effect is neglected and the scale of the

125 wavelet transform method is so large that the amplitude loss is large.

126 Meanwhile, a group of scholars conducted studies on the propagation characteristics of acoustic

127 waves. Hunaidi ^[24] conducted experiments using plastic water pipes and found that the amplitude of

128 the signals attenuate with the propagation distance at a speed of 0.25 dB/m. Muggleton ^[25] analyzed

129 the mechanism of propagation behavior of sound and vibration waves and established the

130 propagation model of signals. Liu ^[26] studied the attenuation characteristics of the wave of a

131 fluid-filled pipeline and concluded that longitudinal waves attenuate more slowly in the pipeline.

132 However, the studies on the attenuation model are insufficient.

133 In this paper, the propagation model of dynamic pressure waves considering the influence of the gas

134 flowing effect will be studied. Then, based on the established model, the location method, which

135 does not take into account velocity and time differences, is proposed and compared with the

136 traditional method that is based on velocity and time differences.

137 2 Materials and methods

138 2.1 Methods of leak detection and location based on amplitude

139 Leak detection should be first accomplished, as in Fig. 2(a), by processing the measured signals to

140 acquire p_{n1} , p_{n2} (kPa). If any one of $p_{n1} / p_{A0} \geq p_A / p_{A0}$, $p_{n2} / p_{A0} \geq p_A / p_{A0}$ is satisfied, a leak

141 exists. In the formula, p_{A0} (kPa) is the reference pressure and p_A / p_{A0} is the threshold value, both

142 of which can be obtained using the test experiment with the smallest leakage orifice, as in Fig. 2(b).

143 When leakage occurs at one end, the acoustic waves are measured at two ends; p_{A0} is the one

144 measured at the same end, which can be calculated using the aero-acoustics theory ^{[20][27]}. All of the

145 amplitudes are acquired through the wavelet transform (WT) method ^{[28][29]}.

146 To verify the WT method, the actual signals of field pipelines are measured. The first dynamic

147 pressure sensor is located downstream 65 cm away from the leakage point, and the other is installed

148 20 km away. The signals are measured at 1000 Hz. The energy of leakage signals is mainly

149 concentrated at 0~50 Hz. With respect to the WT, the relationship between the sampling rate SR (Hz)
 150 and the scale s is:

$$151 \quad SR / 2^{s+1} \leq 50 \quad (1)$$

152 With a scale of 4, the sub-band frequency range is 0~31.25 Hz. The characteristics of the WT
 153 analyses are presented in Table 2.

154 When leakage occurs, the leakage characteristics can be extracted using the WT method, which can
 155 cover a long distance.

156 First, the basic equations of acoustic waves can be established [23][30].

$$157 \quad \frac{\partial^2 p}{\partial t^2} - c_0^2 \frac{\partial^2 p}{\partial x^2} = 0 \quad (2)$$

158 The equation of the three-dimensional acoustic wave is illustrated as follows in the
 159 Cartesian coordinates:

$$160 \quad \frac{\partial^2 p}{\partial t^2} - c_0^2 \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) p = 0 \quad (3)$$

161 When the radiation is constrained within the cylindrical pipe, formula (3) can be expressed under the
 162 cylindrical coordinates as follows:

$$163 \quad \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial p}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 p}{\partial \theta^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} \quad (4)$$

164 The equation of the plane wave is one-dimensional, and the dynamic pressure is illustrated as
 165 follows:

$$166 \quad p(x, t) = p_a e^{j(\omega t - k_0 x)} \quad (5)$$

167 where p_a (Pa) is the amplitude of the acoustic pressure: ω (Hz) is the angular frequency;
 168 $k_0 = \omega / c_0$ is the wave number of undamped waves: and c_0 (m/s) is the velocity of the acoustic
 169 wave.

170 Thus, the pressure waves propagating in the gas pipelines can be described by equation (5), which is

171 simplified. However, in an actual situation, a dissipative process will lead to attenuation, in which a
 172 damping effect ^{[31][32]} (including viscous absorption and heat conduction) should be considered.

173 The equation with the visco-thermal absorption coefficient is obtained ^{[23][30]} as follows:

$$174 \quad p = p_0 e^{-\alpha x} e^{j(\omega t - k_0 x)} \quad (6)$$

175 In equation (6), α is the damping absorption coefficient that describes the attenuation speed of the
 176 amplitude with the distance: x (m) is the propagation distance; and p_0 (Pa) is the absolute amplitude
 177 value generated at the leakage point.

178 In addition to the visco-thermal absorption effects, the fluid flowing effects should also be
 179 considered. As a result, the basic equations of acoustic waves can be expressed as ^[33] :

$$180 \quad \left[\frac{D^2}{Dt^2} - c^2 \frac{\partial^2}{\partial x^2} + 2(\alpha c + \xi U) \frac{D}{Dt} \right] p = 0 \quad (7)$$

181 where $\xi = F/2D$; $F = f(\text{Re})$; F is Froude's number, which is the function of Reynolds number;

182 $\text{Re} = UD\rho_0/\mu$; ρ_0 (kg/m³) is the gas density; μ (Pa·s) is the dynamic viscosity coefficient; U (m/s)
 183 is the fluid velocity; D (m) is the diameter; and c (m/s) is the average velocity of the acoustic wave.

184 Equation (7) assumes the same form as equation (2) with the addition of the carrying effect term of
 185 uniform flowing and the friction term between the flow and the pressure waves. The solution form is
 186 assumed following the expression:

$$187 \quad p(x, t) = C e^{j\omega t} e^{\beta x} \quad (8)$$

188 where β is the exponent coefficient with which the propagating solution follows equation (8).

189 Substituting (8) for (7) and considering

$$190 \quad M^2 \alpha^2 < \alpha^2 \ll k^2, \quad \xi^2 M^4 < \xi^2 M^2 \ll k^2, \quad 2\xi M^3 \alpha < 2\xi M \alpha \ll k^2 \quad (9)$$

191 yields

$$192 \quad \beta^\pm = \mp \left(\frac{\alpha + \xi M + jk}{1 \pm M} \right) \quad (10)$$

193 Therefore, the solution to equation (7) is:

$$p(x, t) = \left[C_1 \exp\left(-\frac{\alpha + \xi M + jk}{1 + M} x\right) + C_2 \exp\left(+\frac{\alpha + \xi M + jk}{1 - M} x\right) \right] e^{j\omega t} \quad (11)$$

In the above equations, C , C_1 , C_2 represent undetermined coefficients; $M = U / c_0$ is the Mach number; and k is the wave number. Compared with equation (7), the amplitude attenuation of equation (11) including the distance is described by equation (12):

$$p(x) = p_0 \exp\left(-\frac{\alpha + \xi M}{1 + M} x\right) \quad (12a)$$

$$p(x) = p_0 \exp\left(\frac{\alpha + \xi M}{1 - M} x\right) \quad (12b)$$

It is evidenced that the amplitude attenuation law follows the exponential curve. Based on equations (12a) and (12b), the propagation principle along the pipeline is obtained, as presented in Fig. 3.

Based on Fig. 3, two equations can be combined as follows:

$$p(x) = p_0 \exp\left(-\frac{\alpha + \xi M}{1 \pm M} |x|\right) \quad (13)$$

The attenuation coefficients (ACs) are then expressed as:

$$\alpha^+ = \frac{\alpha + \xi M}{1 + M} = \frac{\alpha(M)}{1 + M} \quad (14)$$

$$\alpha^- = \frac{\alpha + \xi M}{1 - M} = \frac{\alpha(M)}{1 - M} \quad (15)$$

where α^+ is the attenuation coefficient when the wave propagates in the same direction as the fluid flow, while α^- is the attenuation coefficient when the wave propagates in the opposite direction.

$\alpha(M) = \alpha + \xi M$ represents the actual value of the attenuation coefficient in the flowing fluid and

includes the turbulent effect. $1 \pm M$ represent the Doppler effect resulting from the uniform flow.

α can be obtained as follows:

$$\alpha = \frac{1}{rc_0} \sqrt{\frac{\eta' \omega}{2\rho_0}} + \frac{\omega^2}{2\rho_0 c_0^3} \cdot \eta'' + \frac{\omega^2}{2\rho_0 c_0^3} \cdot \chi \left(\frac{1}{c_v} - \frac{1}{c_p} \right) \quad (16)$$

213 where χ (W/(m·K)) denotes heat conductivity; η' (Pa·s) is the shear viscosity coefficient;
 214 η'' (Pa·s) represents volume viscosity; c_v (kJ/(kg·K)) is the constant-volume specific heat;
 215 c_p (kJ/(kg·K)) is the constant-pressure specific heat; and r (m) is the inner diameter of the pipe.

216 As presented in Fig. 3, it can be concluded that

$$217 \quad p_1 = p_0 \exp\left(-\frac{\alpha + \xi M}{1 - M}|x|\right) \quad (17)$$

$$218 \quad p_2 = p_0 \exp\left[-\frac{\alpha + \xi M}{1 + M}(L - |x|)\right] \quad (18)$$

219 Here, p_1 (kPa) is the amplitude of the signal measured by the upstream sensor, and p_2 (kPa) is the
 220 signal measured by the downstream sensor.

221 Thus, a new leak location method is proposed:

$$222 \quad |x| = \frac{\ln(p_2 / p_1) + \alpha^+ L}{\alpha^+ + \alpha^-} \quad (19)$$

223 where L (m) is the distance between the two sensors. If the gas flowing velocity is so small that it
 224 can be ignored, equation (19) can be expressed as:

$$225 \quad |x| = \frac{\ln(p_2 / p_1) + \alpha(M)L}{2\alpha(M)} = \frac{L}{2} + \frac{\ln(p_2 / p_1)}{2\alpha(M)} \quad (20)$$

226 Compared with the traditional method, the proposed method is simpler. The newly proposed method
 227 focuses on the amplitude of the pressure waves, and cares little about velocity and time difference. In
 228 the traditional method, the amplitude of the pressure waves is used to calculate the time difference,
 229 while in the new method, it is used directly to locate leakages.

230 2.2 Leak detection and location experiments

231 Because the field pipeline section is still working, it is necessary to establish the experimental
 232 facility.

233 2.2.1 Establishing an experimental facility

A laboratory scaled high-pressure gas pipeline loop is established after similarity analyses of field transportation pipelines, as presented in Fig. 4. The internal diameter of the pipeline is 42 mm and the length is 203.0 m. The leak flow rate is controlled via a valve and the orifice. The low frequency response of the dynamic pressure sensor is 0.5 Hz. In the experiments, the natural gas can be replaced by air.

2.2.2 Experiments for leak detection and location

When leakage point 2, 3, or 4 leaks, sensor 1 is regarded as the starting sensor and sensor 3 is regarded as the end sensor, between which the distance is 136.2 m. The distances between leakage points 2, 3, 4 and sensor 1 are 40.30 m, 88.30 m and 128.30 m, respectively. When leakage point 1 leaks, sensors 1 and 3 are used. However, the location of sensor 1 is then changed, and the distances between sensors 1, 3 and leakage point 1 are 12 m and 136.3 m, respectively. When leakage point 5 leaks, sensor 2 is regarded as the starting sensor and sensor 4 is considered the end sensor. The distances between sensors 2, 4 and leakage point 5 are 136.3 m and 11.7 m, respectively. The sampling rate is 3000 Hz, The temperature is 298 K, and the operation pressures are 390 kPa, 820 kPa, and 1150 kPa.

All experiments are conducted using both the traditional and new leak location methods, and the mechanism is presented in Fig. 5.

3 Results and discussion

3.1 Leak detection

When the leakage signals are used to conclude the ACs, the amplitude attenuates due to the gas absorption and pipe interferences as the wave propagates, which is covered by the increasing noise. Hence, the leakage signals measured by the farthest sensor are completely obscured. Though they are processed by the WT, it is difficult to extract the precise amplitude. Therefore, three sensors are used to conclude the ACs without including the farthest one. This means that when leakage point 1 leaks, as in the test, the waves propagate downstream and sensors 1, 2, and 3 are used without sensor 4, but

when leakage point 5 leaks, as in the test experiment, the waves propagate upstream and sensors 4, 3, and 2 are used without sensor 1. In this case, the sensor that is the farthest from the leakage point will not be used because the amplitude weakens significantly as noise becomes increasingly stronger. Thus, because sensor 4 is the farthest one, sensor 3 is regarded as the end sensor. In the experiments, the smallest leakage orifice is 0.10 mm and the lowest pressure level is 390 kPa. Considering the larger noises, a scale of 6 is applied in the WT method, from which the characteristics are extracted. The threshold value is set at 0.1403/0.2286 and p_{A0} is set at 0.2286 kPa. According to the leak detection results presented in Table 3, it can be concluded that all of the leakages can be detected by both methods.

3.2 The location methods

After detecting a leak, the characteristics extracted using the WT method are applied as input variables in the cross-correlation algorithm to calculate the time difference for the traditional method. The propagation velocity of the pressure waves can then be calculated. Regarding the new method, the theoretical ACs are obtained based on equations (14), (15) and (16), and the experimental ACs are obtained through experimental fitting, as presented in Table 4. Table 4 indicates that even the flowing velocity is low and α^+ is close to α^- , the flowing effect must be considered. The leak location error is equal to the ratio of the difference between the calculated and the actual distance to the distance between sensors 1 and 3. The leak location results obtained by the two methods are presented in Table 5. It is determined that the errors using traditional method are small, i.e., most are approximately 0.1%, though the largest is -0.780%. The errors result from the calculation inaccuracies of time differences and velocity. To reduce these errors, more sensors are necessary to measure additional pressures and temperatures, as they are necessary to calculate a more accurate velocity and ensure data synchronization.

284 The errors calculated using the theoretical ACs for locating leaks range, for the most part, from 0.1%
285 to 1%, though the largest error is 2.055%. Conversely, the errors calculated using the experimental
286 ACs for locating leakages arrange from 0.001% to 0.01%, with the largest error being 0.054%.
287 Though there are various ways to calculate the location errors generated by ACs, errors associated
288 with theoretical ACs are generally larger.

289 The errors presented herein result from two factors. (1) There are elbows, valves, and so on through
290 which the amplitudes of the waves attenuate faster than they do through a straight pipeline, but the
291 theoretical ACs are calculated based on a straight pipeline. This means that the amplitude will not
292 strictly obey the same exponential laws. Therefore, to reduce errors, the amplitude attenuation law
293 should be studied further when the acoustic waves propagate through the various pipe elements. (2)
294 When the ACs are calculated via the equations, the parameters are assigned as the mean values of the
295 two ends sensors, though in reality, they vary throughout the total length of the pipeline. Thus, when
296 considering the length of the pipeline, the mean values of the starting and end sensors do not
297 represent the actual condition. Hence, to reduce the errors, more pressure and temperature sensors are
298 necessary to calculate more accurate mean values. The new method actually requires a small
299 percentage of extra sensors in comparison that of the traditional method because the velocity
300 calculation of the traditional method requires more sensors.

301 The later errors result from the inaccuracy of the amplitude, which, in turn, results from the
302 measurement of the original signals and the limitations of the signal-processing method. The errors
303 are also generated during the fitting process of the experimental data. Therefore, to reduce the errors,
304 the acoustic sensors and the WT method should be improved, both of which are also key factors
305 influencing the data synchronization of the traditional method.

306 However, the errors of the new method calculated using the experimental ACs are smaller, generally,
307 than the errors obtained using the traditional method. Thus, it is concluded that the new method is
308 effective when the ACs are obtained via experimental fitting or theoretical calculations that use more

309 accurate parameters.

310 Conclusions are also drawn from the results of the experiments using 10 mm pipelines, where the
311 largest location error is -0.768% for the traditional method and -0.669% for the new method using
312 experimental ACs at 1 MPa, as presented in Table 6.

313 To verify the influence of the flowing gas on locating the leak, equation (20), in which the flowing
314 gas is ignored, is applied. The results are presented in Table 7.

315 It is determined that the location errors are large, i.e., approximately 10%.

316 Though the errors exist, the new method is able to detect and locate leakages. The key factors
317 influencing the accuracy are the amplitude extraction and the calculation of ACs, indicating that
318 these factors require greater attention in the future. Thus, it is concluded that the new method, which
319 is based on amplitude, is more promising.

320 When comparing the new location method with the traditional method, it is determined that they
321 have much in common. For example, both need to conduct test experiments to obtain the threshold
322 value for leak detection; both should be adjusted to satisfy the changing operation situations, such as
323 changes in acoustic velocity due to changes in pressure and changes in ACs due to changes in
324 pressure; and both require accuracy with respect to extracted amplitude, the traditional one, which
325 calculates the time difference, and the new one, which directly calculates the location point.

326 4 Conclusions

327 The following conclusions can be drawn regarding the leak detection and location methods based on
328 the propagation model of waves considering the gas flowing effect in the gas pipeline.

329 (1) All leakages in gas pipelines can be detected by the proposed methods. The largest location error
330 when using the traditional method is -0.780%. The largest errors when using the new method with
331 the theoretical and experimental ACs are 2.055% and 0.054%, respectively.

332 (2) When the traditional method is applied, the new method can also be applied. In 42 mm pipelines,
333 when the experimental ACs are applied, the location errors are smaller than those of the traditional

method. Considering that the experimental ACs are obtained by the test experiments that are necessary for both methods, from the perspective of time and money, the new method is superior to the traditional one. If it is difficult to determine the experimental ACs, the calculation of the theoretical ACs may need more sensors to achieve the same precision as the traditional method. The cost of the new method, considering the extra sensors and the excluded devices, should be compared with the cost of the traditional method according to actual situations. However, it is difficult to achieve a good synchronization of data for the traditional method, and thus, it may require additional investments. Thus, if location precision is desired, the new method should be the first choice based on conciseness and feasibility.

(3) The new method, which is based on amplitude, is more promising and can provide a new approach to the detection and location of leakages in gas pipelines. Further studies should be conducted to address situations where multiple leakages occur in pipelines.

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424 **The collected table and figure captions**

425 Table 1 Evaluation indexes of leak detection and location methods

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432 [Fig. 1](#) The diagram of leak detection

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436 [Fig. 5](#) The diagram of leak location methods

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Table 1 Evaluation indexes of leak detection and location methods

The leak detection method	Sensitivity	Location accuracy	False alarm rate	Missing alarm rate	Detection time	Cost	Total score
Fault tree analysis	1	3	4	2	2	3	15
Negative pressure method	3	4	3	3	3	3	19
Transient model method	4	4	3	4	3	2	20
Mass/volume balance method	4	4	3	4	3	3	21
Hybrid technique	4	4	4	3	4	3	22
Acoustic method	5	5	3	5	5	3	26
Method based on dynamic pressure wave	5	5	4	5	5	3	27

Table 2 Characteristics of WT analyses under different conditions

Diameter of leakage orifice/mm	Number	Amplitude/kPa				A4 by the other sensor to A8 in Jixian
		original signal measured in Jixian	A4 in Jixian	A4 by the other sensor	A4 to original signal measured in Jixian	
10	1	0.2300	0.1574	0.0953	68.45	60.52
	2	0.2250	0.1548	0.0935	68.79	60.38
7	1	0.2200	0.1516	0.0919	68.91	60.60
	2	0.2160	0.1485	0.0898	68.75	60.49
5	1	0.2090	0.1436	0.0867	68.69	60.42
	2	0.2000	0.1378	0.0831	68.88	60.29

Table 3 Leak detection for 42 mm gas pipeline

Leakage point	Operating pressure/MPa	Leakage orifice/mm	p_{A0} /kPa		Amplitude of WT signal/kPa		Leakage or not (judged by experiment)	Leakage or not (judged by simulation)
			Experiment	Simulation	Starting sensor	End sensor		
Point 1	0.4	0.1	-0.2286	-0.1985	-0.2187	-0.1668	Yes	Yes
		0.5			-0.1922	-0.1466	Yes	Yes
		1.0			-0.3091	-0.2359	Yes	Yes
	0.8	0.1			-0.4308	-0.3730	Yes	Yes
		0.5			-0.3976	-0.3443	Yes	Yes
		1.0			-0.5781	-0.5005	Yes	Yes
	1.2	0.1			-0.6887	-0.6033	Yes	Yes
		0.5			-0.6385	-0.5593	Yes	Yes
		1.0			-0.8243	-0.7220	Yes	Yes

Point 2	0.4	0.1	-0.1970	-0.1832	Yes	Yes
		0.5	-0.1731	-0.161	Yes	Yes
		1.0	-0.2785	-0.2589	Yes	Yes
	0.8	0.1	-0.4098	-0.3917	Yes	Yes
		0.5	-0.3782	-0.3616	Yes	Yes
		1.0	-0.5499	-0.5257	Yes	Yes
	1.2	0.1	-0.6580	-0.6311	Yes	Yes
		0.5	-0.6100	-0.5851	Yes	Yes
		1.0	-0.7875	-0.7553	Yes	Yes
Point 3	0.4	0.1	-0.1650	-0.2046	Yes	Yes
		0.5	-0.1450	-0.1799	Yes	Yes
		1.0	-0.2333	-0.2893	Yes	Yes
	0.8	0.1	-0.3765	-0.4152	Yes	Yes
		0.5	-0.3475	-0.3832	Yes	Yes
		1.0	-0.5052	-0.5572	Yes	Yes
	1.2	0.1	-0.6089	-0.6658	Yes	Yes
		0.5	-0.5645	-0.6173	Yes	Yes
		1.0	-0.7287	-0.7968	Yes	Yes
Point 4	0.4	0.1	-0.1424	-0.2244	Yes	Yes
		0.5	-0.1251	-0.1973	Yes	Yes
		1.0	-0.2013	-0.3173	Yes	Yes
	0.8	0.1	-0.3508	-0.4359	Yes	Yes
		0.5	-0.3237	-0.4023	Yes	Yes
		1.0	-0.4707	-0.5849	Yes	Yes
	1.2	0.1	-0.5708	-0.6961	Yes	Yes
		0.5	-0.5292	-0.6453	Yes	Yes
		1.0	-0.6831	-0.8331	Yes	Yes
Point 5	0.4	0.1	-0.1382	-0.2225	Yes	Yes
		0.5	-0.1215	-0.1955	Yes	Yes
		1.0	-0.1954	-0.3145	Yes	Yes
	0.8	0.1	-0.3458	-0.4339	Yes	Yes
		0.5	-0.3192	-0.4004	Yes	Yes
		1.0	-0.4641	-0.5822	Yes	Yes
	1.2	0.1	-0.5635	-0.6931	Yes	Yes
		0.5	-0.5224	-0.6426	Yes	Yes
		1.0	-0.6744	-0.8295	Yes	Yes

Table 4 The attenuation coefficients in 42 mm pipelines

Temperature/K	Operating pressure /kPa	Center frequency/Hz	Gas velocity in positive flowing direction/m/s	Gas velocity in positive flowing direction/m/s	α^+ calculated by equation	α^- calculated by equation	α^+ obtained through experiments	α^- obtained through experiments
298	390	11.71875	0.565	1.845	0.002243	0.003582	0.002310	0.003690
298	820	11.71875	0.031	0.451	0.001189	0.001741	0.001213	0.001768
298	1150	11.71875	0.139	0.602	0.001074	0.001556	0.001114	0.001615

Table 5 Leak location results of two methods in 42 mm pipelines

Leakage point	Operating pressure /kPa	Leakage orifice /mm	Traditional method		New method based on equation (19)			
			Location point/m	Location error/%	ACs obtained by experiments		ACs calculated by equation	
					Location point/m	Location error/%	Location point/m	Location error/%
Point 1	390	0.1	12.303	0.204	11.977	-0.016	10.631	-0.923
		0.5	11.784	-0.146	12.003	0.002	10.657	-0.905
		1.0	12.311	0.210	12.023	0.016	10.679	-0.891
	820	0.1	12.406	0.274	12.025	0.017	11.019	-0.661
		0.5	12.511	0.345	12.033	0.022	11.027	-0.656
		1.0	12.304	0.205	12.011	0.007	11.005	-0.671
	1150	0.1	11.845	-0.105	12.012	0.008	10.209	-1.208
		0.5	11.798	-0.136	12.011	0.008	10.208	-1.208
		1.0	12.411	0.277	11.995	-0.003	10.191	-1.220
Point 2	390	0.1	39.720	-0.426	40.333	0.024	39.978	-0.236
		0.5	39.509	-0.580	40.359	0.044	40.005	-0.216
		1.0	39.920	-0.279	40.274	-0.019	39.918	-0.281
	820	0.1	39.710	-0.433	40.268	-0.024	39.853	-0.328
		0.5	39.720	-0.426	40.364	0.047	39.951	-0.256
		1.0	39.509	-0.580	40.324	0.017	39.910	-0.286
	1150	0.1	39.590	-0.522	40.303	0.002	39.748	-0.405
		0.5	40.160	-0.103	40.326	0.019	39.773	-0.387
		1.0	40.270	-0.022	40.300	0.000	39.745	-0.407
Point 3	390	0.1	87.868	-0.317	88.289	-0.008	89.375	0.789
		0.5	87.868	-0.317	88.382	0.060	89.470	0.859
		1.0	87.788	-0.376	88.294	-0.005	89.380	0.793
	820	0.1	87.588	-0.523	88.243	-0.042	88.664	0.267
		0.5	87.868	-0.317	88.226	-0.054	88.646	0.254
		1.0	87.868	-0.317	88.286	-0.010	88.707	0.299
	1150	0.1	88.649	0.256	88.333	0.025	89.587	0.945

Point 4	390	0.5	88.558	0.190	88.363	0.046	89.617	0.967
		1.0	88.068	-0.170	88.336	0.026	89.589	0.947
		0.1	128.118	-0.134	128.235	-0.047	130.521	1.631
	820	0.5	128.078	-0.163	128.372	0.053	130.662	1.735
		1.0	128.689	0.285	128.279	-0.015	130.566	1.664
		0.1	127.237	-0.780	128.282	-0.014	129.399	0.807
	1150	0.5	128.118	-0.134	128.343	0.032	129.462	0.853
		1.0	128.078	-0.163	128.289	-0.008	129.407	0.813
		0.1	128.218	-0.060	128.319	0.014	131.077	2.039
		0.5	128.699	0.293	128.280	-0.015	131.037	2.010
		1.0	128.528	0.168	128.340	0.029	131.099	2.055
	390	0.1	136.879	0.391	136.332	0.022	138.726	1.639
		0.5	136.777	0.322	136.295	-0.003	138.688	1.613
		1.0	136.768	0.316	136.315	0.010	138.708	1.627
	820	0.1	135.548	-0.508	136.332	0.021	137.493	0.806
		0.5	135.606	-0.469	136.288	-0.008	137.448	0.775
		1.0	136.789	0.330	136.272	-0.019	137.432	0.765
	1150	0.1	136.812	0.346	136.273	-0.018	139.152	1.927
		0.5	135.199	-0.744	136.291	-0.006	139.170	1.939
		1.0	136.540	0.162	136.283	-0.011	139.162	1.934

Table 6 Leak location results of two methods in 10 mm pipelines

Pressure /MPa	Leakage orifice /mm	Number of sensors	Actual distance /m	Traditional method		New method with experimental ACs	
				Location point/m	Location error/%	Location point/m	Location error/%
1	0.1	2					
		3	48.20	48.169	0.350	47.929	-0.148
		4	109.00	47.988	-0.011	47.415	-0.537
		5	160.39	47.281	-0.448	46.927	-0.669
	0.45	2					
		3	48.20	48.169	0.350	48.112	0.232
		4	109.00	48.159	0.146	48.011	0.010
		5	160.39	46.768	-0.768	47.395	-0.377
	0.9	2					
		3	48.20	48.340	0.705	47.741	-0.537
		4	109.00	47.988	-0.011	48.023	0.021
		5	160.39	10.516	-23.371	47.860	-0.087

Table 7 Leak location results of new method based on equation (20) in 42 mm pipelines

Leakage point	Operating pressure/kPa	Leakage orifice/mm	New location method based on equation (20)			
			Attenuation coefficients obtained by experiments		Attenuation coefficients calculated by equation	
			Location point	Location error	Location point	Location error
			/m	/%	/m	/%
Point 1	390	0.1	28.878	11.381	27.523	10.467
		0.5	28.891	11.390	27.536	10.476
		1.0	28.987	11.454	27.634	10.542
	820	0.1	25.773	9.288	24.947	8.730
		0.5	25.818	9.318	24.993	8.761
		1.0	25.749	9.271	24.922	8.713
	1150	0.1	25.584	9.160	23.773	7.939
		0.5	25.568	9.149	23.756	7.927
		1.0	25.541	9.131	23.728	7.908
Point 2	390	0.1	55.963	11.500	55.600	11.233
		0.5	55.990	11.520	55.628	11.254
		1.0	55.905	11.457	55.540	11.189
	820	0.1	52.931	9.274	52.672	9.084
		0.5	53.028	9.345	52.771	9.156
		1.0	52.987	9.315	52.729	9.126
	1150	0.1	52.788	9.169	52.217	8.750
		0.5	52.812	9.186	52.241	8.768
		1.0	52.785	9.167	52.214	8.747
Point 3	390	0.1	104.048	11.562	105.124	12.353
		0.5	104.141	11.630	105.220	12.423
		1.0	104.052	11.566	105.129	12.356
	820	0.1	100.955	9.292	101.516	9.703
		0.5	100.938	9.279	101.499	9.691
		1.0	100.998	9.323	101.560	9.735
	1150	0.1	100.872	9.230	102.094	10.127
		0.5	100.901	9.252	102.124	10.150
		1.0	100.874	9.232	102.096	10.129
Point 4	390	0.1	144.101	11.601	146.377	13.272
		0.5	144.238	11.702	146.519	13.376
		1.0	144.145	11.633	146.422	13.306
	820	0.1	141.034	9.349	142.279	10.264
		0.5	141.096	9.395	142.342	10.310
		1.0	141.042	9.355	142.287	10.270
	1150	0.1	140.901	9.252	143.615	11.245
		0.5	140.862	9.223	143.575	11.215

Point 5	390	1.0	140.922	9.267	143.637	11.261
		0.1	153.583	11.678	155.966	13.288
		0.5	153.486	11.612	155.867	13.221
	820	1.0	153.535	11.645	155.917	13.254
		0.1	150.210	9.399	151.511	10.278
		0.5	150.107	9.329	151.406	10.207
	1150	1.0	150.130	9.344	151.430	10.223
		0.1	149.938	9.215	152.770	11.128
		0.5	149.968	9.235	152.801	11.149
		1.0	149.935	9.213	152.767	11.126

Fig. 1 Diagram of leak detection

(a) process to detect leaks

(b) process to determine threshold values

Fig. 2 The fundamental of leak detection

Fig. 5 Diagram of leak location methods