processes

MDPI

Article

A Leak Identification Method for Product Oil Pipelines Based on Flow Rate Balance: Principles and Applications

Likun Wang [1], Qi Wang [2], Hongchao Wang [1], Min Xiong [1], Shoutian Jiao [2] and Xu Sun [2,*]

[1] PipeChina Institute of Science and Technology, Tianjin 300450, China; wanglk01@pipechina.com.cn (L.W.); wanghc05@pipechina.com.cn (H.W.); xiongmin2001@sina.com (M.X.)
[2] National Engineering Laboratory for Pipeline Safety, China University of Petroleum-Beijing, Beijing 102249, China; wq200006@163.com (Q.W.); jiaost200004@163.com (S.J.)
* Correspondence: xsun@cup.edu.cn

Abstract

To address the data acquisition limitations of traditional flow balance methods that stem from insufficient flow rate measurements, this study establishes a pipeline flow calculation model based on the pressure data and proposes a pipeline leak identification approach for product oil pipelines. Firstly, field leak tests are designed and conducted on a product oil pipeline in East China by discharging oil in a valve chamber to simulate the leak process. Subsequently, combining the Bernoulli equation with the Leapienzon formula, a calculation model is established for flow rate prediction using the pressure data monitored at the stations and valve chambers along the pipeline. By analyzing the instantaneous flow rate changes at each pipeline section and pressure drops at each station and valve chamber, a dual-parameter collaborative threshold is set based on the flow balance principle, and leaks are identified when both parameters exceed the threshold simultaneously. Finally, the proposed flow rate calculation model and leak identification method are validated with respect to the field test data. The results show that the flow rate model yields a relative error as low as 0.48%, and the leak identification method accurately captured all six leak events in the field test, indicating very good stability and accuracy, with great potential for leak identification and alarm systems for product oil pipelines in engineering applications.

Keywords: product oil pipeline; leak identification; flow balance method; Leapienzon formula; flow rate calculation

check for updates

Academic Editor: Qingbang Meng

Received: 18 June 2025
Revised: 29 July 2025
Accepted: 31 July 2025
Published: 4 August 2025

Citation: Wang, L.; Wang, Q.; Wang, H.; Xiong, M.; Jiao, S.; Sun, X. A Leak Identification Method for Product Oil Pipelines Based on Flow Rate Balance: Principles and Applications. *Processes* **2025**, *13*, 2459. https://doi.org/10.3390/pr13082459

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

It is well known that pipelines have significant advantages of higher throughput, reduced product loss, and superior safety performance in transporting product oils, compared to other transportation modes, such as oil tank truck, oil tank train, and oil tanker transportation. With the continuous growth of newly constructed pipelines and the progressive degradation of old pipelines in service, leak problems of product oil pipelines have become more and more significant. Additionally, fatal accidents happen from time to time all over the world, due to reasons such as corrosion, landslide, mis-operation, oil theft through hole drilling, third-party damage, etc. [1]. For example, in December 2003, a pipeline rupture took place in the Lan-Cheng-Yu Pipeline in China due to illegal tapping for oil theft, resulting in direct economic losses of approximately RMB 4.4 million. In December 2009, a diesel spill incident occurred in the Lan-Zheng-Chang Pipeline in China, during which a significant volume of diesel was released into the Chi River, causing severe water

contamination. Therefore, investigating identification and alarm methods to promptly and accurately detect leaks and eliminate the incidents they may induce is of great practical importance for the safe operation of product oil pipelines.

Many studies have been carried out on leak identification in oil pipelines in recent decades. Isermann and Siebert [2] applied digital low-pass filtering to flow signals measured at both ends of a pipeline, computed the cross-correlation function, and implemented threshold-based criteria to detect pipeline leaks. Stouffs and Giot [3] proposed a leak detection approach based on real-time monitoring of the dynamic equilibrium between the mass flow rate difference and the packing term variation at the pipeline inlet and outlet. Al-Shidhani et al. [4] developed a wavelet-based leak severity monitoring method to capture the singularities in reflected pressure waves under abnormal events. Sattar and Chaudhry [5] presented a new technique for detecting pipeline leaks using the frequency response of pipelines, which does not require previous transient data before the leak and is easy to apply. Martins and Seleghim [6] demonstrated that the flow balance method, in comparison to the acoustic method, not only exhibits superior capability in detecting progressive leaks caused by corrosion or slow crack growth but also provides more precise quantification of leak rates. Yang et al. [7] proposed a leak detection model based on the three conservation laws in hydromechanics and the state equation, consisting of a transient simulation model and a volume balance model. Santoso et al. [8] proposed a pipeline leak detection system for two-phase flow based on an artificial neural network (ANN). Ostapkowicz [9] developed identification methods based on negative pressure waves and pressure gradients, enabling a satisfactory level of efficiency for the diagnosis of single leaks. Wang et al. [10] designed and applied a transient-based leak detection method using the matched-field processing (MFP) technique, which is able to estimate the location and size of leaks despite uncertainty of the fluid–pipe system wave speed. Liu et al. [11] proposed a leak detection method based on extracting Markov features from pressure data and designed a two-stage decision scheme employing a distance indicator as a switch for the least square support vector machine classifier to detect pipeline leaks. Fu et al. [12] performed leak detection experiments to obtain pressure and flow data at the pipeline inlet and outlet, with the leak position identified via dimensionless analysis. Banjara et al. [13] found that support vector machines and relevance vector machines, when combined with acoustic emission features, can effectively be utilized for the identification and localization of leak in pipelines. Wang et al. [14] proposed a pipeline leak detection and localization method by integrating the compressed sensing theory with a fiber Bragg grating pipe-fixture sensor array, which improved localization accuracy and stability without increasing the number of sensors. Fu et al. [15] proposed a leak identification approach for parallel pipelines based on flow parameter analysis. Their method integrated computational fluid dynamics (CFD) simulations and analyzed the correlation between pressure drop and flow rate through a mathematical model. Peng et al. [16] proposed a percussion-based approach for pipeline leak detection with improved MobileNet Version 2, which effectively enhanced the accuracy of leak detection by introducing a multi-scale feature fusion module. Cai et al. [17] proposed a novel leak detection model based on the real-time transient model and transfer learning, which has a high online leak detection capability under complex operating conditions. Ma et al. [18] proposed a novel leakage detection and localization algorithm for oil pipelines by integrating wavelet denoising with a long short-term memory (LSTM)-transformer model, and conducted an experimental test on the Jilin-Changchun long-distance oil pipeline. Ismail et al. [19] discussed the applicability of industry 4.0 technologies in oil and gas pipeline leakage monitoring. Zhang et al. [20] proposed a leak sensing method for offshore oil pipeline using acoustic emission signals and machine learning. Song et al. [21] developed a fusion recognition model of an LSTM optimized by a

one-dimensional convolutional neural network (1DCNN) and dung beetle optimization algorithm (DBO) for oil and gas pipeline leak detection. Pahlavanzadeh et al. [22] studied the detection and localization of multiple leaks in long-distance oil pipelines using a two-stage decision-making scheme.

In previous studies, different models have been proposed for leak detection in oil pipelines based on variation features of the flow rate and pressure induced by leaks, which depend on high-precision measurements of flow parameters along the pipeline. In real engineering applications, however, the real-time pressure and flow rate data of high-accuracy are not always available at each section of an oil pipeline. On the one hand, because pipeline flowmeters of high precision are much more expensive than pressure meters and are only installed at pumpstations, the flow rate data measured along the oil pipeline is usually not as adequate as the pressure data. On the other hand, even the pressure data monitored along the oil pipeline may have poor time correlation due to the inconsistency of pressure meters at the pump stations and valve chambers, resulting in additional errors in leak identification, especially for older pipelines with higher leak risk. To solve these problems, the proposed leak identification methods have to be modified before they are applied to real engineering application scenarios.

In the present paper, an improved leak identification method based on flow rate balance is proposed for product oil pipelines by taking into account the lack of flow rate data and error of monitored pressure data in real engineering applications. Using this method, a computational model of flow rate using real-time pressure data is derived based on the Bernoulli equation and Leapienzon formula for incompressible pipe flow, pipeline leaks are identified based on the flow difference between the upstream and downstream pipe sections and pressure drops at the pipe inlet and outlet, and errors in flow rate and pressure measurements are amended using the data before a leak occurs. To examine the accuracy of the proposed method, a field leak test was conducted on a product oil pipeline in East China, and the predicted results are compared with the experimental data. The leak identification method proposed and the results presented are valuable for the safe operation and accident prevention of product oil pipelines.

2. Mechanics Model and Mathematical Formulation

Figure 1 illustrates the leak model of a product oil pipeline system. As seen in Figure 1a, a product oil pipeline system consists of many pumping stations, valve chambers, and the pipeline sections between them. At each pumping station, both the pressure and flow rate are measured, while in the valve chamber, only the pressure is usually monitored. As seen in Figure 1, when a leak appears in one section of the pipeline, both the flow rate and the pressure in the pipe drop abruptly at the leaking point, leading to a rearrangement of the flow parameters in the pipe. By monitoring variations in the pressure and/or flow rate, the leak problem in product oil pipelines can be identified.

For product oil pipelines, the incompressible flow model can be applied. In cases without branches or leaks, the flow rates at different sections are identical. When a leak occurs, as seen in Figure 1a, the relationship between the flow rates can be expressed as

$$Q_A = Q_{leak} + Q_C \tag{1}$$

where Q_A is the volume flow rate in the pipe upstream of the leaking point, m^3/s; Q_{leak} is the leak flow rate, m^3/s; Q_C is the volume flow rate in the pipe downstream of the leaking point, m^3/s.

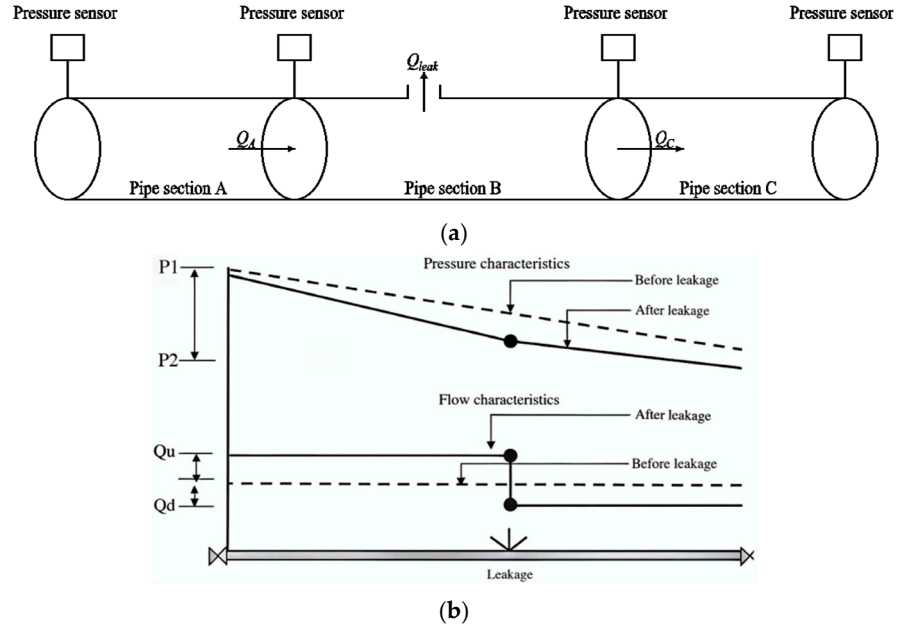


Figure 1. Schematics of the product oil pipeline leak process. (**a**) Process flow diagram of a product oil pipeline system. (**b**) Effects of leak on the pressure and flow rate of the pipeline.

According to Equation (1), the leak can be identified easily by monitoring the flow rate along the product oil pipeline. In engineering applications, however, Equation (1) cannot be used directly in most scenarios due to several reasons. Firstly, compared with monitoring the pressure signal, prompt and precise measurements of the flow rate are much more expensive. Therefore, the flow rate of the pipeline is usually monitored in the pump station by Venturi or ultrasonic flowmeters, while it is not measured in the valve chambers. Therefore, the measured flow rate data are usually insufficient for leak identification. Secondly, compared with the distance between the valve chambers, the distance between two adjacent pump stations is much larger and usually up to hundreds of kilometers, leading to poor temporal synchronization between the flow rate data from two stations. Therefore, a threshold for the flow rate difference between two adjacent pump stations is usually employed when Equation (1) is applied for leak identification to take into account the error and temporal asynchronization of the measured flow rate data.

Compared to flow rate measurement, pressure measurement in the product oil pipeline system is easier and costs significantly less. Therefore, pressure sensors are installed at both the pump stations and valve chambers to obtain instantaneous pressure data of high accuracy for leak identification. To express the flow rate using pressure data monitored along the pipeline, the Bernoulli equation for incompressible pipe flow is combined with the Leapienzon formula. Following the Bernoulli equation, the energy conservation along a product oil pipeline can be expressed as

$$z_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + h_f \tag{2}$$

where z is the elevation of the pipe with respect to the sea level, m; p is the pressure, Pa; v is the averaged flow velocity of the cross section, m/s; h_f is the fractional head loss per unit weight of fluid, m; 1, 2 stand for two different cross sections. Usually, the diameter of the pipeline (D) is fixed between two adjacent pump stations, and the flow rate in one section is fixed due to the mass conservation law when there is no leak. As a result, the averaged flow velocity at each cross section is identical, namely, $v_1 = v_2$. Moreover, the fractional

head loss h_f can be calculated by the Leapienzon formula. As a result, Equation (2) can be rewritten as

$$p_1 - p_2 = \rho g(z_2 - z_1) + \rho g \beta \frac{l Q^{2-m} \nu^m}{D^{5-m}} \quad (3)$$

where Q is the flow rate, m^2/s; l is the length of the pipeline, m; ν is the kinematic viscosity, m^2/s; β and m are coefficients that vary with the flow state, as shown in Table 1, where $\varepsilon^* = 2\Delta/D$ and Δ is the roughness of the pipe's inner surface. Using Equation (3), the relationship between the pressure and flow rate is established, and thus the flow rate in the pipe can be calculated using the pressure data measured from the pump stations and chamber valves, the geometric parameters of the pipeline (l, z and Δ), and the fluid properties (ρ and ν). The pipeline flow calculation model applies to incompressible flow and is suitable for both laminar and turbulent flows. The pipeline diameter (D) is fixed between adjacent pump stations, ensuring uniform cross-sectional flow velocity ($v_1 = v_2$) under non-leak conditions (consistent with mass conservation).

Table 1. Selection of parameters in the Leapienzon Formula.

Flow Regime		Range of Reynolds Number	β	m
Laminar flow		$Re < 2100$	4.15	1
Turbulent flow	Hydraulically smooth	$2100 \leq Re < \frac{59.7}{(\varepsilon^*)^{\frac{8}{7}}}$	0.0246	0.25
	Mixed friction	$\frac{59.7}{(\varepsilon^*)^{\frac{8}{7}}} \leq Re < \frac{665-765\lg\varepsilon^*}{\varepsilon^*}$	0.0826λ	0
	Hydraulically rough	$Re \geq \frac{665-765\lg\varepsilon^*}{\varepsilon^*}$	0.0826λ	0

3. A Leak Identification Method Based on Flow Rate Balance

3.1. Calculation of the Flow Rate

In product oil pipeline systems, high-precision pressure sensors are usually installed at critical monitoring nodes along both the upstream and downstream sections (e.g., pump stations and valve chambers) to collect real-time dynamic pressure signals at a sampling frequency of 20 Hz. Based on the measured pressure data and Equation (3), a leak identification method for product oil pipeline is developed following the principle of flow rate balance.

Firstly, the flow rate in a section of pipeline is calculated using the pressure data measured at the inlet and outlet by following the solution procedure in Figure 2: (1) Input pressure data (p_1, p_2), pipeline geometric parameters (D, l, z_2-z_1), and oil physical properties (ρ, ν). (2) Assume a fluid flow regime. (3) Determine the parameter β and m in the Leapienzon formula following the assumed regime and Table 1. (4) Compute the flow rate (Q) using Equation (3). (5) Verify the flow regime using the computed flow rate: if the newly computed flow regime coincides with the assumed one, end the computation and output the flow rate; otherwise, update the assumed regime, go back to step (2), and repeat the computation until the flow rate is obtained.

3.2. Leak Identification Method

Using the computed flow rate (Q) and measured pressure (p_1, p_2), a leak identification approach for the product oil pipeline is proposed based on a quantitative analysis of transient pressure-drop amplitudes and dynamic increments in flow rate differences between upstream and downstream sections. As seen in Figure 3, the leak identification process primarily consists of the following steps:

(1) Obtain the real-time pressure data from the pressure sensors at the pump stations and valve chambers, and compute the flow rate at each pipeline section following the solution procedure in Figure 2.

(2) Compare the flow rates of the adjacent pipeline sections. For the target pipeline section, compute the flow rate difference between the upstream pipeline and downstream pipeline, namely, $\Delta Q = Q_u - Q_d$. Take into account the errors from the measured pressure data and from the solution procedure of Q in Figure 2, and correct ΔQ using the initial flow rate difference when there is no leak (ΔQ_0), namely, $\Delta Q' = \Delta Q - \Delta Q_0$

(3) Compute the pressure drops at the inlet and outlet of the target pipeline section by $\Delta p_1 = p_1^{n+1} - p_1^n$ and $\Delta p_2 = p_2^{n+1} - p_2^n$, where the superscript n stands for the monitoring time point, and subscripts 1 and 2 represent the inlet and outlet points.

(4) Identify the leak using the following criteria: a leak occurs in a pipeline section when the difference in flow rates between its upstream and downstream sections exceeds a specified threshold of δ_Q, and at the same time, the pressure drops at its two ends exceed the thresholds of δ_{p_1} and δ_{p_2}, namely, $(\Delta Q' > \delta_Q) \cap (\Delta p_1 < -\delta_{p_1}) \cap (\Delta p_2 < -\delta_{p_2})$.

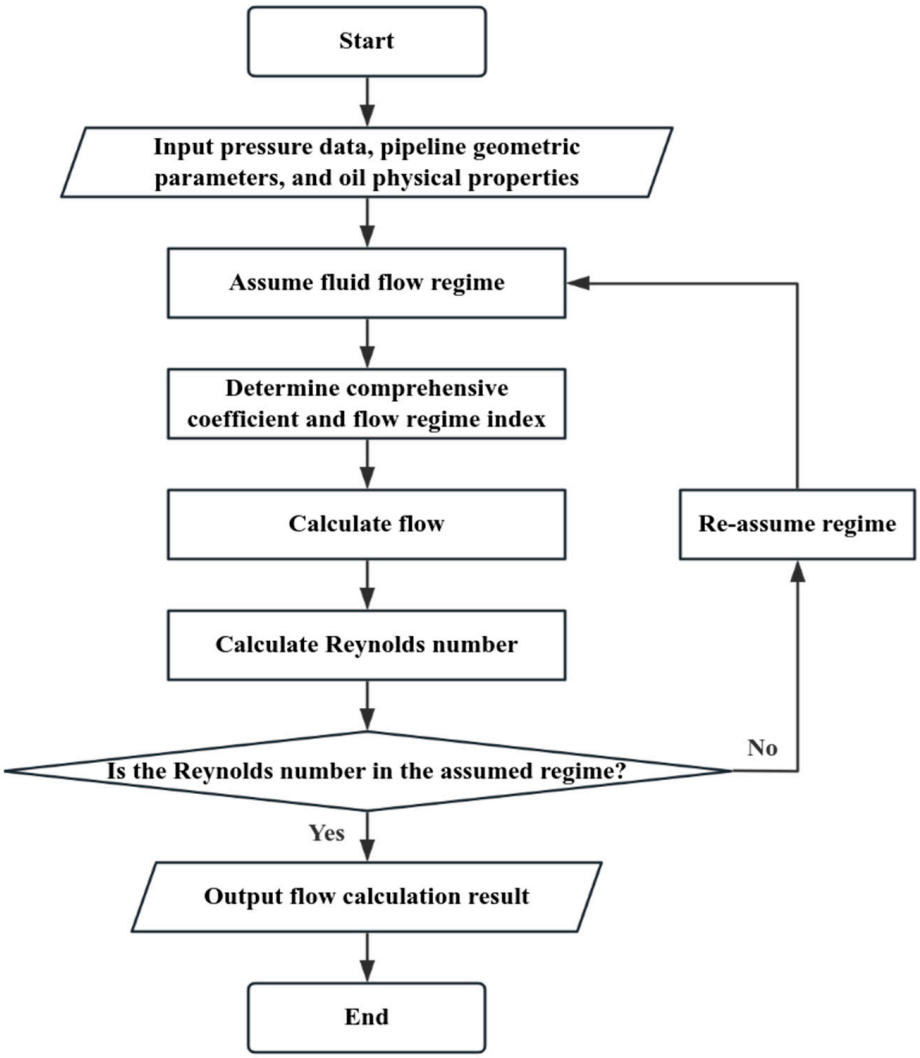


Figure 2. Flowchart of flow rate computation in a product oil pipeline using the measured pressure data.

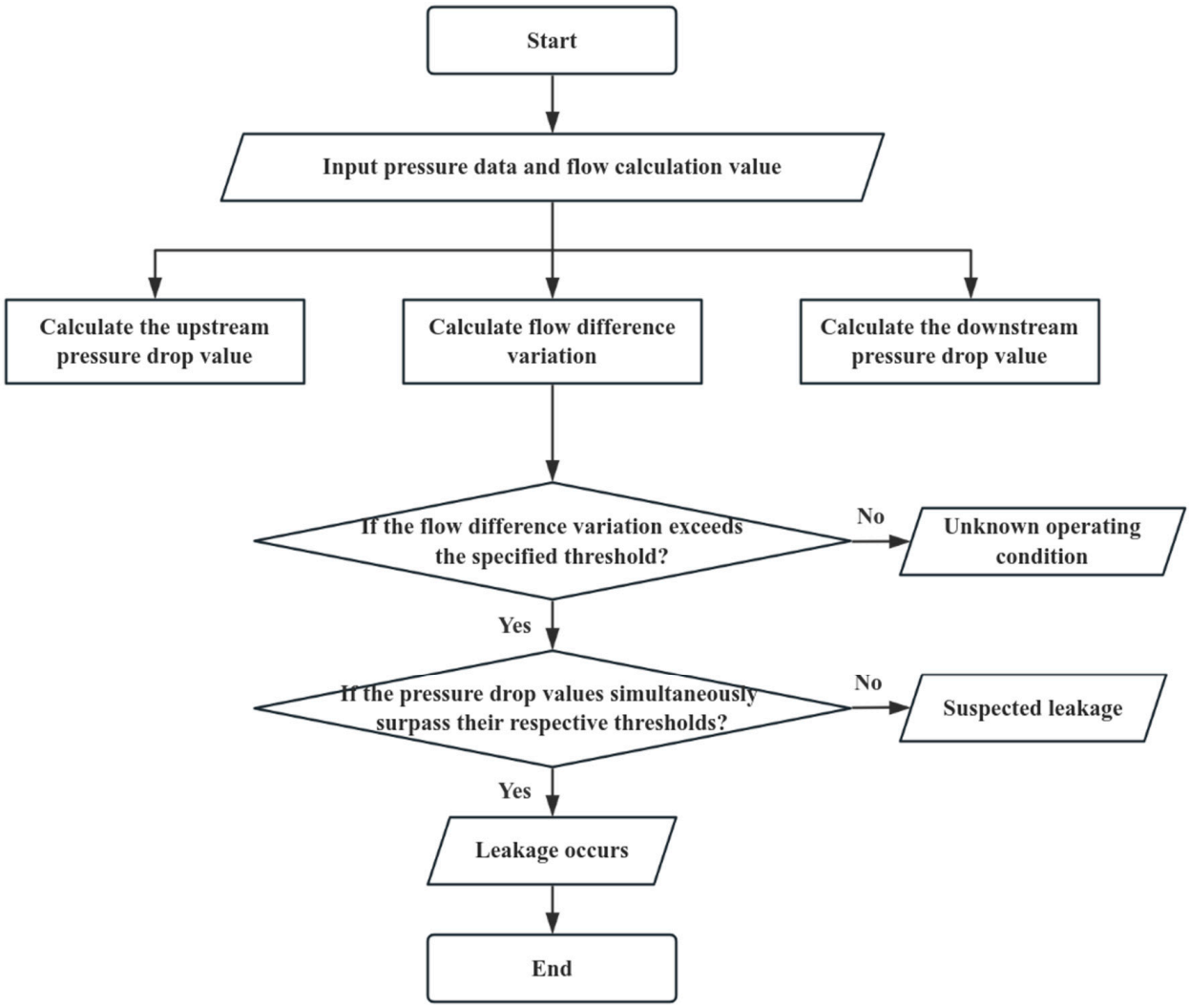


Figure 3. Flowchart for leak identification in a product oil pipeline.

4. Applications and Validations

4.1. Field Tests to Measure Leaks in Product Oil Pipelines

To validate the accuracy and effectiveness of the proposed flow rate computation method and leak identification method for product oil pipeline proposed in Section 3, a field leak test was designed and conducted on a product oil pipeline in East China. As seen in Figure 4, the pipeline consists of 8 stations (Initial Station, Pigging Station 1, Pumping Station 1, Branch Station 1, Pigging Station 2, Pumping Station 2, Branch Station 2, and Terminal Station) and 18 pipeline block valve chambers (10 remotely controlled valve chambers and 8 manually operated valve chambers). The product oil pipeline has a designed transportation capacity of 3.0×10^6 t/a, a total trunk length of 615 km, and operates under a design pressure of 8 MPa. Employing a closed-loop batch transportation process, the pipeline sequentially conveys 0-grade diesel, 5-grade diesel, 10-grade diesel, 90-grade gasoline, and 93-grade gasoline.

A controlled oil discharge test was conducted to simulate pipeline leak conditions at Valve Chamber 3 in Section (7) of the pipeline between Pigging Station 2 and Pumping Station 2, as indicated by the red box in Figure 4. Section (7) spans 40.078 km, and the test point was located at 11.842 km downstream the Pigging Station 2 and 28.236 km upstream the Pumping Station 2. During the leak test, the transported medium in the pipeline was always diesel, and the mainline flow rate on the inlet of the tested pipe section was

270 m^3/h. The other geometric and flow parameters are presented in Table 2. The leak was simulated by discharging the oil in the Valve Chamber 3 through a needle valve at the pressure gauge tapping point. During the testing period from 13:19 to 15:16, six oil discharge tests were carried out using ball valves of different orifice diameters. As seen in Table 3, for the first five leak tests, the opening/closing speed of the valve was fast, and the valve was fully opened/closed in 5 s. For the last leak test, however, the opening/closing time was increased to 1 min. In the last column of Table 3, the discharged volume in each test is also presented.

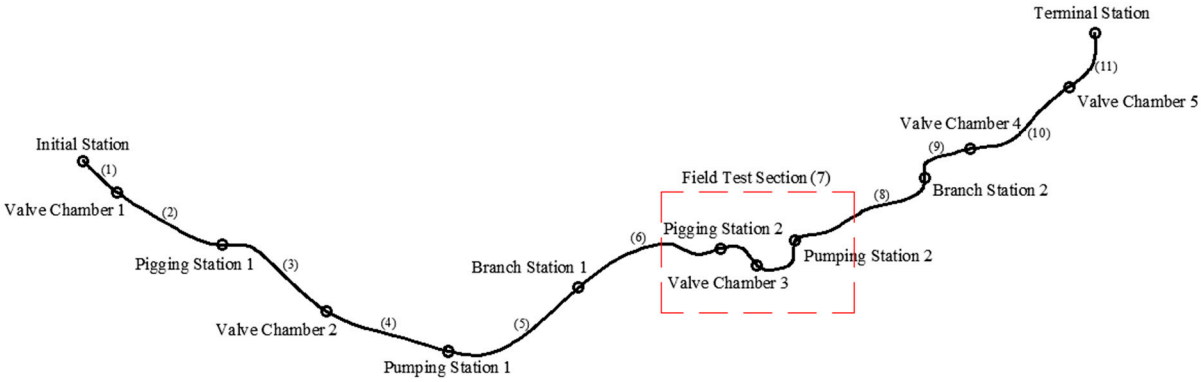


Figure 4. Schematic of the product oil pipeline employed for the leak test.

Table 2. Parameters of the leak experiments in the pipeline segment between Pigging Station 2 to Pumping Station 2.

Station and Valve Chamber	Mileage (km)	Spacing (km)	Elevation (m)	Internal Diameter (mm)	Pipeline Transport Medium	Density (kg/m^3)	Viscosity (m^2/s)
Pigging Station 2	355.710	-	59.80				
Valve Chamber 3	367.552	11.842	80.20	273.1	Diesel	847.4	4.72×10^{-6}
Pumping Station 2	395.788	28.236	72.50				

Table 3. Results of oil leak test monitored in Valve Chamber 3.

Serial Number	Valve Opening Speed (s)	Valve Opening Time	Valve Closing Time	Discharge Volume (m^3)
1	5	13:19	13:29	0.29
2	5	13:49	13:57	0.37
3	5	14:16	14:19	0.14
4	5	14:29	14:32	0.13
5	5	14:42	14:45	0.11
6	60	14:49	15:16	1.04

Figure 5 provides the instantaneous pressure monitored at the Pigging Station 2 upstream the leak point and at the Pumping station 2 downstream the leak point during six leak tests, where the red line indicates the starting point of each leak test, and the open circles stand for the leak time predicted by our prediction method proposed in Section 3. As seen in the figure, when leak/discharge occurred in the pipeline section, the pressures upstream and downstream the leak point dropped continuously over time. Because the leak point was closer to the pigging station, the pressure at Pigging Station 2 dropped a little bit earlier than that at Pumping Station 2, as shown clearly in Figure 5c–e. For the last leak test, the valve was opened much more slowly, resulting in a smoother pressure drop in the pipeline, as seen in Figure 5f.

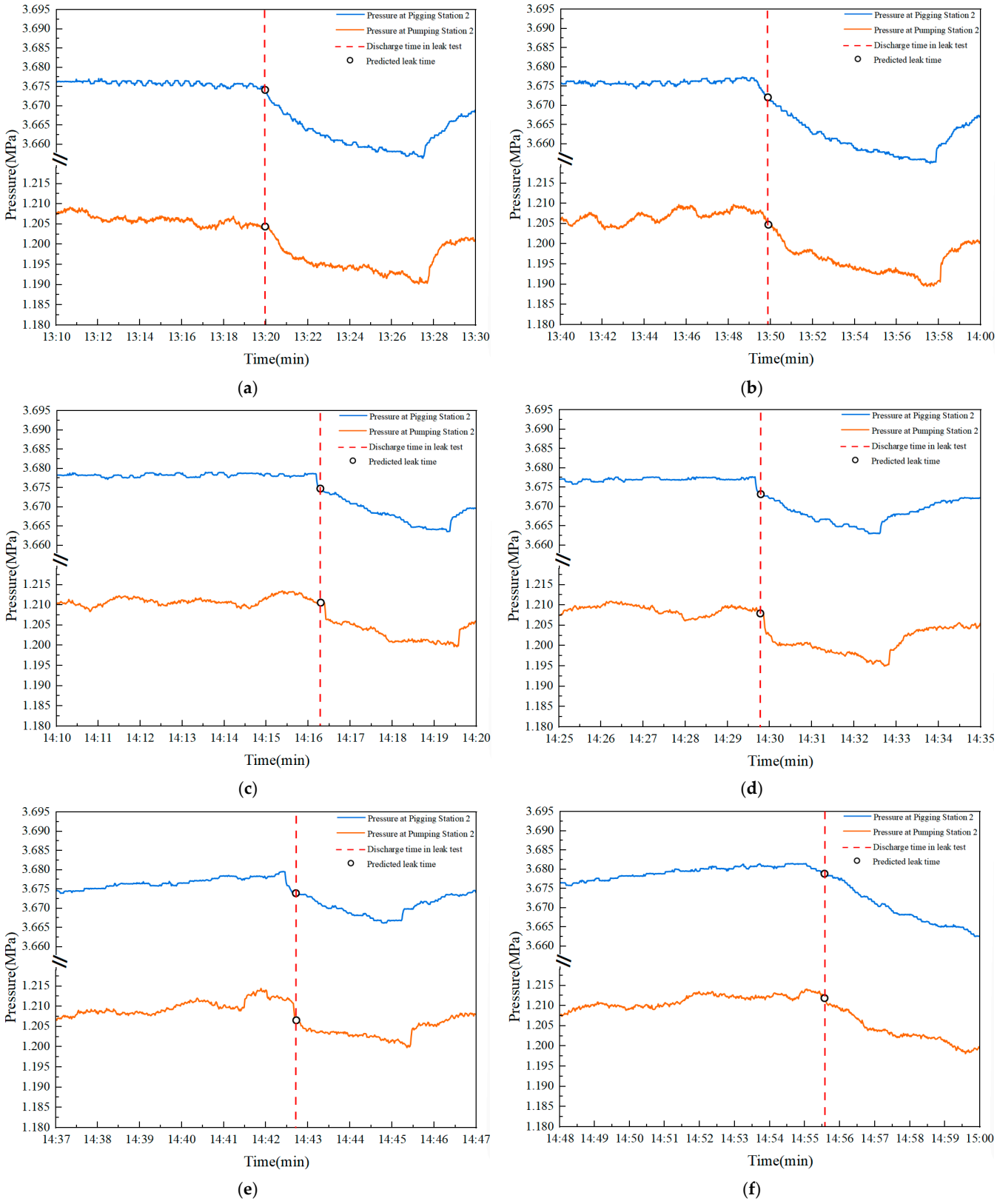


Figure 5. Instantaneous pressure monitored at Pigging Station 2 to Pumping Station 2 during six leak tests. (**a**) First oil discharge test. (**b**) Second oil discharge test. (**c**) Third oil discharge test. (**d**) Fourth oil discharge test. (**e**) Fifth oil discharge test. (**f**) Sixth oil discharge test.

4.2. Application and Validation of the Proposed Leak Identification Method

Following the flow condition of the field leak tests, the real-time acquired pressure data were substituted into the pipeline flow calculation model proposed in Section 3.1. The Reynolds number of the flow in Section (7) of the pipeline at time 14:01 was Re = 76,918, indicating that turbulent flow was in the hydraulically smooth region, with β = 0.0246 and m = 0.25. The computed flow rate was Q = 268.70 m^3/h, representing a relative error of 0.48% compared to the measured flow rate of 270 m^3/h. Therefore, the proposed model for flow rate computation based on the pressure signals along the pipeline has high accuracy.

Following the leak identification method proposed in Section 3.2, leaks can be identified in product oil pipelines when the flow rate difference exceeds the specified threshold δ_Q, and at the same time, the pressure drops at both ends of the pipeline section simultaneously surpass their thresholds δ_{p1} and δ_{p2}, respectively. According to the scheduling manual of the product oil pipeline employed for the field leak test, these thresholds are set as δ_Q = 0.5 m^3/min, δ_{p1} = 0.0007 MPa, and δ_{p2} = 0.0008 MPa, respectively.

Tables 4 and 5 show the computed flow rate differences, upstream pressure drops and downstream pressure drops at each pipeline section in the test product oil pipeline at 14:01 and 14:30, respectively. As seen in Table 4, at 14:01, simultaneous exceedances of δ_Q, δ_{p1}, and δ_{p2} did not occur at each pipeline section, indicating there was no leak along the entire pipeline. This is in agreement with the field leak test. As seen in Table 5, at 14:30, the computed flow rate differences in the upstream pressure drop and downstream pressure drop at Section (7) were δ_Q = 0.9274 m^3/min, δ_{p1} = −0.0077 MPa, and δ_{p2} = −0.0064 MPa, respectively. These values all exceed the corresponding thresholds, indicating the occurrence of a pipeline leak in this section, which is in agreement with the leak tests.

Figure 6 shows the variations in the flow rate differences at Section (7) of the product oil pipeline during the oil discharge leak test period. As seen in the figure, the flow rate difference at Section (7) varied with time and exceeded the threshold at time points of 13:20, 13:50, 14:16, 14:30, 14:43, and 14:56, which are consistent with the oil discharge times. The computed leak times of the test pipeline are also presented in Figure 5. As seen in the figure, for all six leak tests, the predicted leak times show very good agreement with the real discharge times, indicating the accuracy of the proposed leak identification method.

Table 4. Computed leak determination parameters at each pipeline section at 14:01.

Pipeline Section	Flow Rate Difference (m^3/min)	Upstream Pressure Drop (MPa)	Downstream Pressure Drop (MPa)
(1)	-	−0.0005	−0.0006
(2)	0.1002	−0.0006	−0.0002
(3)	−0.0597	−0.0004	−0.0003
(4)	−0.0983	−0.0001	−0.0006
(5)	0.1703	0.0013	0.0022
(6)	−0.1210	0.0018	0.0016
(7)	0.1177	0.0015	0.0028
(8)	−0.0466	−0.0008	0.0009
(9)	−0.0531	0.0008	0.0006
(10)	−0.0075	0.0007	0.0002
(11)	0.0114	0.0002	0.0000

Table 5. Computed leak determination parameters at each pipeline section at 14:30.

Pipeline Section	Flow Rate Difference (m^3/min)	Upstream Pressure Drop (MPa)	Downstream Pressure Drop (MPa)
(1)	-	0.0013	0.0003
(2)	0.2324	0.0003	0.0000
(3)	−0.0258	0.0001	−0.0005
(4)	0.6077	−0.0003	0.0029
(5)	−0.4169	−0.0026	−0.0015
(6)	−1.1183	−0.0011	−0.0067
(7)	0.9274	−0.0064	−0.0077
(8)	0.0731	0.0008	0.0002
(9)	0.0217	0.0000	0.0001
(10)	−0.0080	0.0002	0.0002
(11)	−0.0284	0.0001	−0.0003

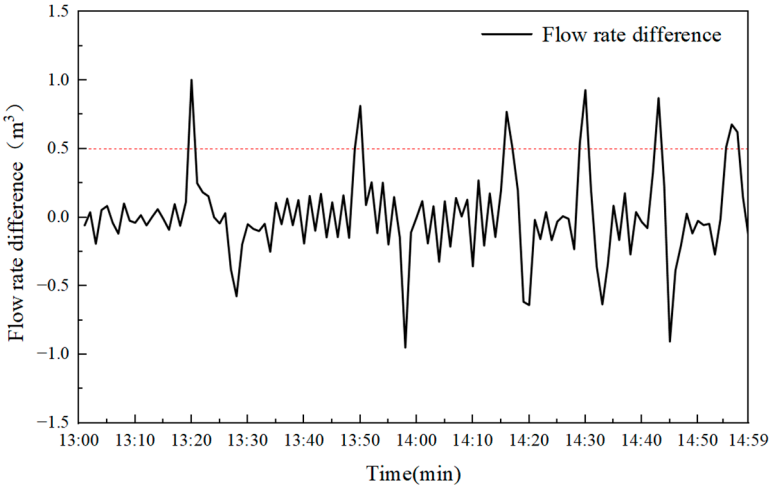


Figure 6. Computed time history of flow rate differences in Section (7) of the pipeline.

5. Conclusions

A leak identification method has been proposed for product oil pipelines based on the flow rate balance principle, and its feasibility and accuracy have been validated using a field leak test. Based on the results obtained, the main contributions/conclusions could be drawn as follows:

(1) Field leak tests were carried out on a product oil pipeline in East China by simulating a leak that discharged oil into a valve chamber. The effects of the leak rate and duration of the leak were investigated through six discharging operations, providing a solid data basis for the validation and development of the leak identification method.

(2) For product oil pipelines, highly accurate instantaneous pressure data is easier to achieve than flow rate data. Therefore, a calculation model for flow rate prediction was established based on the Leapienzon formula and the pressure data monitored at the stations and valve chambers along the product oil pipeline. Comparing the computed flow rate with that measured in the field test, the relative error of the proposed flow rate model was found to be as low as 0.48%.

(3) A leak identification approach was developed by instantaneously analyzing the flow differences between different pipeline sections and the pressure drops at the stations and valve chambers. By applying the proposed method to the tested product oil pipeline with experimental data, it was found that the proposed method was able to precisely capture all six leak operations in the field leak test, indicating its stability and accuracy for real engineering applications.

As a first step toward developing an improved leak identification method to make up for the lack of flow rate data in real applications, this paper mainly focuses on the basic principles, computing models, and validation via field tests, with the pipeline structure under consideration being relatively simple. Next, the method's performance under varying operational or environmental conditions and on more complex networks should be further investigated. In addition, because the Bernoulli equation assumes steady flow, the model proposed here is only applicable to steady-state conditions. Based on the present work, developing a leak prediction model for unsteady operations, such as pump startup and shutdown, distribution, and throttling, is also an important direction for future research.

Author Contributions: Conceptualization, L.W. and X.S.; methodology, L.W. and Q.W.; validation, H.W. and M.X.; formal analysis, L.W. and Q.W.; data curation, S.J.; writing—original draft preparation, L.W.; writing—review and editing, X.S.; visualization, S.J.; supervision, X.S.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Likun Wang, Hongchao Wang, and Min Xiong are employed by the PipeChina Institute of Science and Technology. The remaining authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Weng, Y.; Sun, X.; Yang, Y.; Tao, M.; Liu, X.; Zhang, H.; Zhang, Q. An improved prediction method for failure probability of natural gas pipeline based on multi-layer Bayesian network. *Processes* **2024**, *12*, 2930. [CrossRef]
2. Isermann, R. Process fault detection based on modeling and estimation methods—A survey. *Automatica* **1984**, *20*, 387–404. [CrossRef]
3. Stouffs, P.; Giot, M. Pipeline leak detection based on mass balance: Importance of the packing term. *J. Loss Prev. Process Ind.* **1993**, *6*, 307–312. [CrossRef]
4. Al-Shidhani, I.; Beck, S.; Staszewski, W. Leak monitoring in pipeline networks using wavelet analysis. *Key Eng. Mater.* **2003**, *245*, 51–58. [CrossRef]
5. Sattar, A.M.; Chaudhry, M.H. Leak detection in pipelines by frequency response method. *J. Hydraul. Res.* **2008**, *46*, 138–151. [CrossRef]
6. Martins, J.C.; Seleghim, P., Jr. Assessment of the performance of acoustic and mass balance methods for leak detection in pipelines for transporting liquids. *J. Fluids Eng.* **2010**, *132*, 011401. [CrossRef]
7. Yang, Z.; Liu, M.; Shao, M.; Ji, Y. Research on leakage detection and analysis of leakage point in the gas pipeline system. *Open J. Saf. Sci. Technol.* **2011**, *1*, 94–100. [CrossRef]
8. Santoso, B.; Indarto, I.; Deendarlianto, D. Pipeline leak detection in two phase flow based on fluctuation pressure difference and artificial neural network (ANN). *Appl. Mech. Mater.* **2014**, *493*, 186–191. [CrossRef]
9. Ostapkowicz, P.L. 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. [CrossRef]
10. Wang, X.; Ghidaoui, M.S. Pipeline leak detection using the matched-field processing method. *J. Hydraul. Eng.* **2018**, *144*, 04018030. [CrossRef]
11. Liu, J.; Zang, D.; Liu, C.; Ma, Y.; Fu, M. A leak detection method for oil pipeline based on Markov feature and two-stage decision scheme. *Measurement* **2019**, *138*, 433–445. [CrossRef]
12. Fu, H.; Yang, L.; Liang, H.; Wang, S.; Ling, K. Diagnosis of the single leakage in the fluid pipeline through experimental study and CFD simulation. *J. Pet. Sci. Eng.* **2020**, *193*, 107437. [CrossRef]
13. Banjara, N.K.; Sasmal, S.; Voggu, S. Machine learning supported acoustic emission technique for leakage detection in pipelines. *Int. J. Press. Vessels Pip.* **2020**, *188*, 104243. [CrossRef]
14. Wang, J.; Ren, L.; Jia, Z.; Jiang, T.; Wang, G.X. A novel pipeline leak detection and localization method based on the FBG pipe-fixture sensor array and compressed sensing theory. *Mech. Syst. Signal Process.* **2022**, *169*, 108669. [CrossRef]

15. Fu, H.; Ling, K.; Pu, H. Identifying two-point leakages in parallel pipelines based on flow parameter analysis. *J. Pipeline Sci. Eng.* **2022**, *2*, 100052. [CrossRef]
16. Peng, L.; Zhang, J.; Li, Y.; Du, G. A novel percussion-based approach for pipeline leakage detection with improved MobileNetV2. *Eng. Appl. Artif. Intell.* **2024**, *133*, 108537. [CrossRef]
17. Cai, X.; Wang, J.; Wei, Z.; Ye, Y.; Zhang, L. Transferred real time transient model for online pipeline leakage detection under complex operating conditions. *Geoenergy Sci. Eng.* **2025**, *247*, 213685. [CrossRef]
18. Ma, Y.; Shang, Z.; Zheng, J.; Zhang, Y.; Weng, G.; Zhao, S.; Bi, C. Research on Leak Detection and Localization Algorithm for Oil and Gas Pipelines Using Wavelet Denoising Integrated with Long Short-Term Memory (LSTM)–Transformer Models. *Sensors* **2025**, *25*, 2411. [CrossRef]
19. Taifa, I.W.; Mahundi, R.A.; Mahabi, V. Exploring the applicability of industry 4.0 technologies in oil and gas pipeline leakage monitoring: Results from an empirical study. *J. Ind. Inf. Integr.* **2025**, *46*, 100857. [CrossRef]
20. Zhang, M.; Xu, W.; Xie, Y. A leak sensing method for offshore oil pipeline using acoustic emission signals and machine learning. *Ocean Eng.* **2025**, *336*, 121768. [CrossRef]
21. Song, J.; Yan, R.; Lu, J.; Liu, X.; Yang, D. Research on oil and gas pipeline leak detection method based on 1DCNN-DBO-LSTM. *Meas. Sci. Technol.* **2024**, *36*, 016024. [CrossRef]
22. Pahlavanzadeh, F.; Khaloozadeh, H.; Forouzanfar, M. Oil pipeline multiple leakage detection and localization based on sensor fusion. *Eng. Fail. Anal.* **2024**, *167 Pt B*, 109038. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.