Diagnosis and Localization of Pipeline Leak Based on Fuzzy Decision-making Method[1)]

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Abstract A leak detection plays a key role in the overall integrity monitoring for a oil pipeline system. A fuzzy decision-making approach to pipeline leak localization is proposed in this paper. The two main methods, pressure gradient localization and negative pressure wave localization, are combined with fuzzy logical decision-making method to form a novel fault diagnosis scheme. The combination scheme can improve the precision of localization. An application example, 14km long oil pipeline leak detection and localization, is illustrated. This method is compared with others through practical experiments and its validity is confirmed by the results.

Key words Leak detection and localization, fuzzy decision-making, pressure gradient, negative pressure wave

1 Introduction

With pipeline industry development, there is an increasing demand on safe running and leak detection of oil pipelines[1]. Especially for a long pipeline operating alongside fruitful cropland, a leak detection system is an indispensable condition for its construction. In order to meet this demand, a number of methods have been developed. Their aim is to improve the precision of leak localization and to reduce the detection time. In nature, this is a question of fault diagnosis[2].

There are two main kinds of available methods for pipeline leak detection and localization. The first is the observer method[3,4], namely pressure gradient method. It is sensible to weak leak but not applicable to serious leak. It has a distinct disadvantage that this method has to install many sensors along the pipeline[5]. The second is the negative pressure wave method[6]. It is sensible to serious leak but not applicable to weak leak. It has a distinct advantage that each of the sending and receiving terminals in the pipeline only needs to install one sensor, but its precision of localization is not satisfactory. Because of the complexity of actual leak diagnosis in pipelines, any single method is not sufficient to solve the idiographic problem. There are few papers concerning the combination of multiple methods to solve the actual problem. Motivated by the methods mentioned above and the idea of multi-method combination, we propose a new localization method for the leak of oil pipeline in this paper, which we call a diagnosis and localization approach based on fuzzy decision-making theory (AFDM). This method only need install two sensors at each terminal of the pipeline, and can improve the precision of localization greatly.

2 Detection method

When oil pipeline works normally, the pressure and flow of both the sending and receiving terminals in the pipeline (P_i, P_o, Q_i, Q_o) remain invariable on the whole, where Q_i, Q_o, P_i and P_o denote the mass flow and the pressure of the sending and receiving terminals. According to the principle of mass balance, the flow difference $\Delta Q = Q_i - Q_o$ is near zero. They approximately satisfy normal distribution with means P_{im}, P_{om} and ΔQ_m, respectively. In other words, they all fluctuate in a narrow range centering on their means. The means can be calculated in non-leak status by the following equations.

$$P_{im} = E(P_i) \tag{1a}$$

$$P_{om} = E(P_0) \tag{1b}$$

$$\Delta Q_m = E(\Delta Q) \tag{1c}$$

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where E denotes mathematical expectation. Once leak occurs, the pressure of the sending and receiving terminals (P_i, P_o) will decrease, and the flow difference (ΔQ) will increase. In order to improve detection robustness, we must introduce some thresholds. Perhaps leak happens if the sampled data satisfiy all the following conditions.

$$\bar{P}_i < P_{im} - Threshold(P_i) \tag{2a}$$

$$\bar{P}_o < P_{om} - Threshold(P_o) \tag{2b}$$

$$\Delta\bar{Q} > \Delta Q_m + Threshold(\Delta Q) \tag{2c}$$

where $\bar{P}_i, \bar{P}_o$ and $\Delta\bar{Q}$ denote means of data of a fixed length closed to the time of detecting. The changes of pressure and flow difference before and after leak happens are shown in Fig. 1. To distinguish changing work status from true leak, [7] presented their rules to reduce the ratio of false alarm.

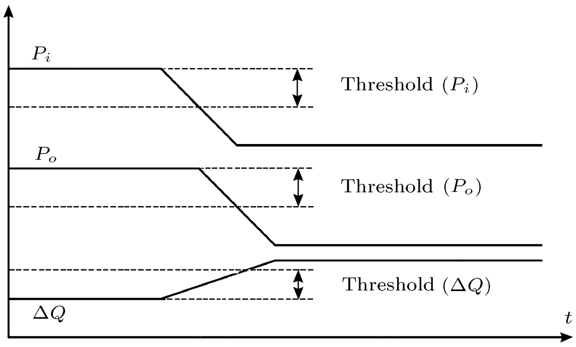


Fig. 1 The changes of pressure and flow difference in pipeline before and after leak appearance

3 Localization method

3.1 Locating using pressure gradient

When oil flows in the pipeline, its status is expressed by pressure, density, velocity, and temperature. Usually, the curvature radius of the pipeline is much bigger than the diameter of pipeline, and the oil density and pipe cross-section area are constant. The continuity and momentum equations are[8]

$$A\frac{\partial \rho}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{3}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{\partial P}{\partial x} + \frac{1}{2A^2\rho}\frac{\partial Q^2}{\partial x} = -\rho g \sin\theta - \frac{2fQ^2}{D\rho A^2} \tag{4}$$

where P is pressure (pa), Q is mass flow (kg/s), ρ is liquid density (kg/m^3), x is length of pipeline (m), t is time (s), g is gravity $(\mathrm{m/s^2})$, A is the cross-section area (m^2), D is the pipeline diameter (m), and f is frication coefficient. Assuming the convective change in velocity and compressibility are negligible, we have

$$\frac{\partial Q}{\partial t} = 0, \quad \frac{\partial Q}{\partial x} = 0 \tag{5}$$

Considering the pipeline is horizontal, predigesting (3) and (4) with (5) yields

$$\frac{\partial P}{\partial x} = -\frac{2fQ^2}{D\rho A^2} \tag{6}$$

The leak at a point, which is $x_f(m)$ away from the sending terminal of the pipeline with outflow

$$Q_{x_f} = \lambda\sqrt{P_{x_f}}, \lambda \geqslant 0 \tag{7}$$

produces a discontinuity in system (3) and (4), so the pipeline with the leak must be handled as two pipelines or two sections with a boundary condition

$$Q^b_{x_f} = Q^a_{x_f} + Q_{x_f} \tag{8}$$

where $Q_{x_f}^b$ and $Q_{x_f}^a$ denote the mass flow at the sections in front of and behind the leak point, Q_{x_f} denotes the outflow. Since the leak modifies behavior of the fluid, the boundary condition (8) only describes the leak effect, the dent′s effect cannot be modeled by only changing the sign of λ for its uncertainty. The space partial differentials with respect to x in (6) can be approximated by

$$\left.\frac{\partial P}{\partial x}\right|_{x\leqslant x_f} = -\frac{2fQ_i^2}{D\rho A^2} \tag{9a}$$

$$\left.\frac{\partial P}{\partial x}\right|_{x_f\leqslant x\leqslant L} = -\frac{2fQ_o^2}{D\rho A^2} \tag{9b}$$

where Q_i and Q_o denote the mass flow of the sending and receiving terminals, L is the pipeline length (m). (9) is the formula of pressure decreasing in each duct. Assuming that the pressure gradients are evenly distributed throughout each duct, we can rewrite (9) as follows.

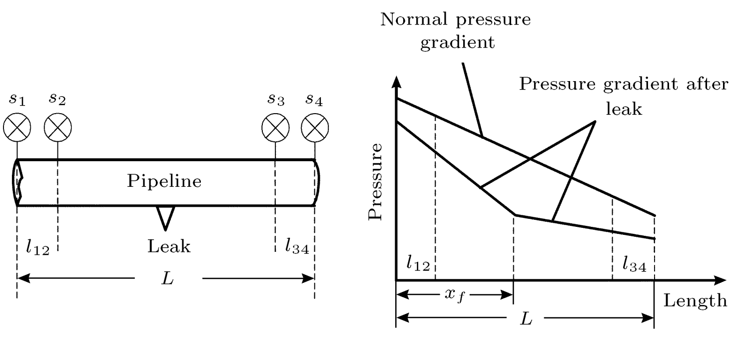
$$\left.\frac{\partial P}{\partial x}\right|_{x\leqslant x_f} = \frac{P_{x_f} - P_i}{x_f} \tag{10a}$$

$$\left.\frac{\partial P}{\partial x}\right|_{x_f\leqslant x\leqslant L} = \frac{P_o - P_{x_f}}{L - x_f} \tag{10b}$$

where P_{x_f}, P_i and P_o denote the pressure of the leak point, sending and receiving terminals, x_f denotes the distance away from the sending terminal. Further, we can get the localization equation

$$x_f \frac{P_o - P_i - L\cdot\left.\frac{\partial P}{\partial x}\right|_{x_f\leqslant x\leqslant L}}{\left.\frac{\partial P}{\partial x}\right|_{x\leqslant x_f} - \left.\frac{\partial P}{\partial x}\right|_{x_f\leqslant x\leqslant L}} \tag{11}$$

[9] mentioned a method by which the space partial differentials could be computed. But they assumed that the parameter f and two terminals′ pressure in the pipeline were constant either before leak happened or after, and used the same parameter f to obtain $\left.\frac{\partial P}{\partial x}\right|_{x\leqslant x_f}$ and $\left.\frac{\partial P}{\partial x}\right|_{x_f\leqslant x\leqslant L}$. Leak may occur at any point. It is a stochastic incident. The pressure and f are not constant in two sections. Moreover, f is much difficult to be obtained. In order to circumvent these, the method of double pressure sensors is proposed. We may install four pressure sensors at two terminals, two (s_1, s_2) in the sending terminal and the other two (s_3, s_4) in the receiving terminal, as shown in Fig. 2(a). The changes of pressure gradient, which occur before and after the leak, are shown in Fig. 2(b).



(a) Pressure sensors in pipeline (b) The changes of pressure gradient

Fig. 2 Pressure sensors and the changes of pressure gradient

The gradient calculated by (10) can be approximated by

$$\left.\frac{\partial P}{\partial x}\right|_{x\leqslant x_f} = \frac{P_{s_2} - P_{s_1}}{l_{12}} \tag{12a}$$

$$\left.\frac{\partial P}{\partial x}\right|_{x_f \leqslant x \leqslant L} = \frac{P_{s_4} - P_{s_3}}{l_{34}} \tag{12b}$$

In engineering practice, the measured pressure value is usually disturbed by noise. If we compute the gradient of two sections using instantaneous measured pressure values, there will bring greater errors. So we compute them with a fixed length of data closed to the time of having detected the leak. Each pressure will be substituted by its mean. So (12) can be revised as follows.

$$\left.\frac{\partial P}{\partial x}\right|_{x \leqslant x_f} = \frac{\bar{P}_{s_2} - \bar{P}_{s_1}}{l_{12}} \tag{13a}$$

$$\left.\frac{\partial P}{\partial x}\right|_{x_f \leqslant x \leqslant L} = \frac{\bar{P}_{s_4} - \bar{P}_{s_3}}{l_{34}} \tag{13b}$$

3.2 Locating using negative pressure wave

Once leak occurs, the leak point can produce a negative pressure wave. This negative pressure wave will transfer toward the upper and lower reaches in oil along the pipeline at a speed $v(m/s)$ of about 1000 m/s. When the wave arrives the inlet and outlet, the pressure at both terminals must decrease. The localization principle of negative pressure wave is that the point of leak can be calculated by the transferring speed of negative pressure wave and time-interval Δt, at which the negative pressure wave arrives at the inlet and outlet of the pipeline. The localization equation is as follows.

$$x_f = \frac{L - v \cdot \Delta t}{2} \tag{14}$$

In the above equation, L is a fixed value for a given pipeline, v can be measured by experimentation, and Δt must be obtained by the exact time at which negative pressure wave arrives at the inlet and outlet of the pipeline. The exact time at which the negative pressure wave arrives at the inlet and outlet of pipeline can be obtained by the method of wavelet analysis[7].

3.3 Fuzzy decision-making method for localization

The basic structure of the proposed fuzzy decision-making localization method to pinpoint leak point is shown in Fig. 3. For leak detection, the input data must be converted into a qualitative fuzzy membership value by fuzzification. There are a variety of choices for membership functions, such as triangle, Gaussian and exponential shape functions.

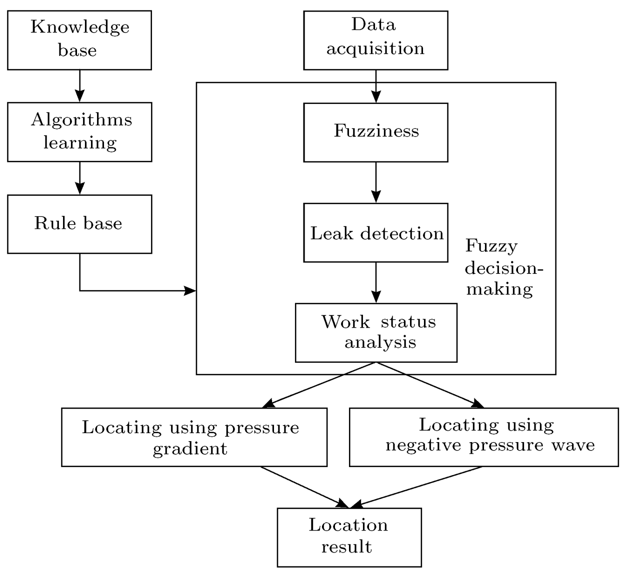


Fig. 3 The structure of fuzzy decision-making localization

A family of fuzzy decision-making rules can be derived from knowledge base, which can be obtained by operator′s experience, and produced by learning algorithms or mechanism analysis. The derived rules form a rule base. Normally, a fuzzy diagnostic rule R_i is form:

$$R_i : IF \quad \textit{Operating status of the transporting pipeline is} \ \ldots,$$
$$THEN \quad \textit{Reasoning result of the work status is} \ \ldots.$$

All of operating status in premise part construct the decision condition space $C = \{c_1,c_2,\ldots,c_j,\ldots,c_m\}$, where c_j denotes the j-th kind of operating status. All of candidate reasoning results in conclusion part construct the decision result space $D = \{d_1, d_2, \ldots, d_i, \ldots, d_n\}$, where d_i denotes the i-th candidate reasoning result. Each kind of operating status has been classified into v degree fuzzy subsets, the membership of the current operating status belonging to each subset is $E = \{e_0, e_1, \ldots, e_k, \ldots, e_{v-1}\}$. e_k describes the k-th degree of operating status deviation from normal state. Each kind of candidate reasoning result has been classified into u degree fuzzy subsets, the membership of the current reasoning result belonging to each subset is $F = \{f_0, f_1, \ldots, f_k, \ldots, f_{u-1}\}$. f_k denotes the degree, in which reasoning result of the current work status belongs to the k-th degree fuzzy subset. The fuzzy decision-making rule table is like the following form.

Table 1 The fuzzy decision-making table

	Decision condition space				Decision result space			
	c_1	c_2	$\cdots$	c_m	d_1	d_2	$\cdots$	d_n
Rule 1	e_i	e_j	$\cdots$	e_k	f_i	f_j	$\cdots$	f_k
Rule 2	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\vdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
Rule n	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$

When the pipeline works normally, there is no obvious deviation from normal state and beyond the accepted range for all c_i in the decision condition space. On adjusting operating status or leak occurring, the normal state will not be maintained[10]. We consider two influence relations as follows.

Relation 1. The deviations of operating status c_j from normal state take on the deviation of all the candidate reasoning results. The influence effect upon the i-th candidate reasoning result can be described by measured matrix as follows.

$$\mu = \begin{pmatrix} \mu_{i10} & \cdots & \mu_{i1(u-1)} \\ \vdots & \ddots & \vdots \\ \mu_{im0} & \cdots & \mu_{im(u-1)} \end{pmatrix}, \ i = 1, 2, \cdots, n, \ \sum_{k=0}^{u-1} \mu_{ijk} = 1, \ i = 1, 2, \cdots, n, \ j = 1, 2, \cdots, m, \ \mu_{ijk} \leqslant 1 \tag{15}$$

Relation 2. For a given candidate reasoning result, the influence effect of all operating status in decision condition space C is different. This can be valued by weight vector as follows:

$$w = \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} = \begin{pmatrix} w_{11} & \cdots & w_{1m} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nm} \end{pmatrix}, \ \sum_{j=0}^{m} w_{ij} = 1, i = 1, 2, \cdots, n, \ j = 1, 2, \cdots, m, \ w_{ij} \leqslant 1 \tag{16}$$

Definition. The term cof_i is a measure vector. That is to say the confidence of d_i belonging to its degree fuzzy subset. It can be calculated by following equations:

$$cof_i = w_i \times \mu_i \tag{17}$$

$$cof = (cof_1 \quad cof_2 \quad \cdots \quad cof_n)^{\mathrm{T}} \tag{18}$$

cof is called as decision identification matrix, by which the confidence of the candidate reasoning results can be measured, so the locating scheme of multi-method combination can be applied.

If d_i denotes leak, it has three degrees: no leak (f_0), weak (f_1) and serious (f_2). cof_{i1} and cof_{i2} describe their confidence, x_{f_1} and x_{f_2} denote localization results of the two methods, then the final localization result is

$$x_f = \frac{cof_{i1} \cdot x_{f1} + cof_{i2} \cdot x_{f2}}{cof_{i1} + cof_{i2}} \tag{19}$$

4 Applications

The approach proposed above was tested to pinpoint leak point in a pipeline, which is in Shengli Oil Field. It is 14.117 km long and with an inner diameter of 273 mm and wall thickness of 7 mm. The oil temperature of sending terminal is 80°C, and the oil temperature of receiving terminal is 45°C. The sending pressure is between $0.4Mpa$ and $0.34Mpa$, and the receiving pressure is between $0.14Mpa$ and $0.12Mpa$. The transporting flow is between $36L/s$ and $33L/s$. To obtain pressure gradient and flow difference, we have installed two high precision pressure sensors and one flow sensor at each terminal of the duct. The distance between two pressure sensors is about 100 $m(l_{12} = 105\ m, l_{34} = 110\ m)$. There was a tap located at 6.15 km away from the sending terminal of the pipeline to imitate true leak.

In the application, the decision condition space consists of 5 operating status, $C = \{c_1, c_2, c_3, c_4, c_5\}$. They denote pressure of the sending terminal (c_1), pressure of the receiving terminal (c_2), flow of the sending terminal (c_3), flow of the receiving terminal (c_4), flow difference (c_5), respectively. Each kind of operating status has 3 degree fuzzy subsets, $E = \{e_0, e_1, e_2\}$. They denote normal (e_0), small deviation (e_1), and serious deviation (e_2), respectively. The decision result space consists of 4 candidate reasoning results, $D = \{d_1, d_2, d_3\}$. They denote normal (d_1), leak (d_2), adjusting valve or startup, and stop of pump (d_3), respectively. Each kind of candidate reasoning result has three degree fuzzy subsets, $F = \{f_0, f_1, f_2\}$. They denote normal (f_0), weak degree (f_1), and serious degree (f_2), respectively.

Fig. 4 shows the membership functions of operating status in decision condition space, which consist of normal, small, and serious. Therefore, the number of the fuzzy decision-making rules should be $3^5 = 243$ at most.

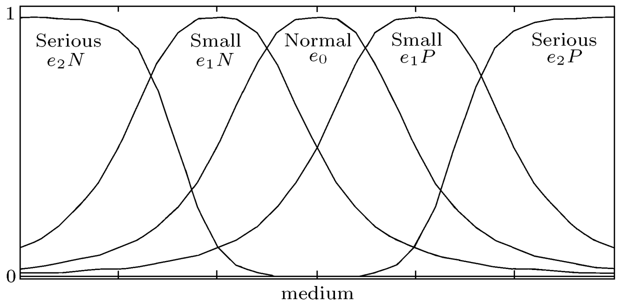


Fig. 4 The membership functions of operating status

The important part of fuzzy decision-making rules is shown in table 2. In table 2, "N" denotes negative deviation, "P" denotes positive deviation, "-" denotes any possible degree.

Table 2 The fuzzy decision-making table of work status analysis

Rule	Decision condition space					Decision result space		
	c_1	c_2	c_3	c_4	c_5	d_1	d_2	d_3
Rule 1	e_0	e_0	e_0	e_0	e_0	f_0	f_0	f_0
Rule 2	e_1N	e_1N	e_1P	e_1N	e_1P	f_1, f_2	f_1, f_2	f_0
Rule 3	e_2P	e_2P	e_2P	e_2P	e_2P	f_1, f_2	f_0	f_1, f_2
Rule 4	e_0	e_0	e_1P	e_1P	e_1P	f_1	f_0	f_1
Rule 5	–	–	–	e_1P	–	f_1, f_2	f_0	f_1, f_2
Rule 6	–	–	–	–	e_2N	f_1, f_2	f_0	f_1, f_2

Tests have been taken 20 times in different operating status successfully. The oil leakage is between 20 m^3/h and 3 m^3/h. The time of leak is between $20s$ and $40s$. All of the leaks could be detected in $10s$ after leak happens. The average localization error is 190 m, which is about 1.35 percent of the the pipeline length. The precision of localization satisfies the need of engineering completely. Table 3 gives the concrete data of the localization results and the comparison. It can be seen that the proposed approach in this paper obtains a better localization precision.

Table 3 The concrete data of the localization results and the comparison

		Methods		
		Pressure gradient[3]	Negative pressure wave[6]	AFDM
Performances	Location(km)	5.6	6.5	5.96
	Absolute error (km)	−0.55	0.35	−0.19
	Relative error (%)	3.8	2.4	−1.35

5 Conclusions

A novel localization approach of fuzzy decision-making (AFDM) combining the method of pressure gradient localization with the method of negative pressure localization has been presented. The proposed method overcomes the disadvantages of using single method. It is clear from practical application that the scheme of combination of two methods by fuzzy decision-making theory achieves satisfactory results. In order to reduce the calculating load and consumption time, in the future work, we intend to adopt the multi-resolution technique based on improved wavelet transform to obtain the exact time at which the negative pressure wave arrives at the inlet and outlet of pipeline.

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