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Parameter Setting of Gas-liquid Linkage Valve in Natural Gas Leakage Detection System

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Abstract: Gas-liquid linkage valve is a core device in leakage detection system of natural gas trunk pipe, the scientific setting of its parameters directly influences the effectiveness and sensitivity of leakage detection system. A leakage model was firstly build based on gas dynamic theory. finally large amount of numerical calculation analysis Results: The nearer the leakage site was from the starting valve of the pipeline, the more decreasing range the pressure at the starting valve would have. The leakage equivalent diameter had a critical value in the premise of unchanged transmission quantity, pressure and diameter. The established multiple fitting formulas had an average calculation error of less than 10% which had important guiding significance for the diagnosis of pipeline leakage.

Key words: Leakage model, pipe leakage detection, pipeline simulation, multiple fitting

INTRODUCTION

The introduction of trunk pipeline leakage detection system provides a powerful guarantee for the safe transmission of the pipeline. The application of gas-liquid linkage valve to the pipeline field and the valve could meet the need of emergency shutoff in case of exceptional conditions for the field and the transportation system. However, what come to us is how parameters of the gas-liquid valve should be scientifically set to ensure the effectiveness and sensitivity of the leakage detection system. The gas liquid linkage valve takes the pressure lowering rate as the control parameter. It is an actual problem the gas transmission company have to cope with whether the trunk pipeline leakage detection system could correctly identify and close the valve in case of accidents and whether the discontinued production status could be settled as soon as possible to prevent the hold of the pressure when the trunk pipeline leakage detection system has an error (Murvay and Silea, 2012; Liang *et al*., 2013). The calculating and monitoring of different leakage detection parameters in different conditions were relatively complex and there are not mature setting rule and judging method all over the world up to now (Zhai *et al*., 2012; Wang and Meng, 2007; Zhang, 2003). To ensure a scientific parameter setting, the author deeply analyzed the pressure changing rate of the starting valve in different conditions and leakage. The quantitative relation and the corresponding law were obtained between the pressure lowering rate of the starting valve and different parameters, including leakage points, pipe diameter, transmission quantity and operating pressure, thus establishing a practical and easy method for the parameter setting of gas-liquid valve and providing guidance for the diagnosis of pipeline leakage.

LEAKAGE MODEL OF GAS PIPELINE

During the numerical analysis on the pipeline, we could consider it as a leakage site with a known changing law of flowing quantity, then the numerical calculation was performed on the leakage conditions of the entire pipeline by the long-distance transportation formula and the pressure changing of the starting valve was calculated and analyzed in different parameters including transportation quantity and leakage equivalent diameter.

Combined with Helena Montiel Model, a mathematical model was build based on equation of state of gas in pipe, equation of mass conservation and energy equation (Reddy *et al*., 2011; Xiang and Feng, 2007; Sang and Lan, 2011). The symbols were set as follows:

$$\begin{cases} Ma_1 p_1 \left(\dfrac{kM}{RT_1}\right)^{1/2} = Ma_2 p_2 \left(\dfrac{kM}{RT_2}\right)^{1/2} = B \\ \left(\dfrac{Y_2}{Y_1}\right)^{1/2} \dfrac{p_0 Ma_2}{p_1 Ma_1} = E \\ 2/k = l \\ k/(k+1) = m \\ p_0/p = m \\ Ma_1/Ma_2 = v \\ Y_1/Y_2 = w \\ A_c/A_{\alpha} = A \\ \left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}} = C \end{cases} \tag{1}$$

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Leakage outflow sound velocity model:

$$\begin{cases} Ap^2\sqrt{\dfrac{MkC}{RT^2}} = B \\ \dfrac{k+1}{2k}\ln\left(v^2w\right) + \dfrac{A^2}{kC}\left(1-v^2\right) + \dfrac{4fL}{D} = 0 \end{cases} \quad (2)$$

Both the in-pipe and outflow were subsonic models 3, when the state parameter of the leakage was in accordance with that in the air:

$$\begin{cases} Ap^2\sqrt{\dfrac{2k}{k-1}\dfrac{M}{RT^2}\left(n^1-n^m\right)} = B \\ \dfrac{k+1}{2k}\ln\left(v^2w\right) + \dfrac{k-1}{2k\left(E^1-E^m\right)}A^2\left(1-v^2\right) + \dfrac{4fL}{D} = 0 \end{cases} \quad (3)$$

When both the in-pipe and the outflow were sonic models, the leakage model was as follows:

$$\begin{cases} Q_v = A_{or}Ma_1p_1\sqrt{\dfrac{MkC}{RT_1}} \\ \dfrac{k+1}{2k}\ln\left[\dfrac{2Y_1}{Ma_1{}^2(k+1)}\right] + \dfrac{A^2}{kC}\left[1-\dfrac{1}{Ma_1{}^2}\right] + \dfrac{4fL}{D} = 0 \end{cases} \quad (4)$$

where, the subscrip "1" stand for the starting point of the pipeline and the subscrip "2" for the leakage site; p_0 was the air pressure; p_i was the pressure at i, in P_a; k was the adiabatic index (dimensionless); Y_i was dimensionless parameter:

$$Y_i = 1 + (k-1)\times\frac{Ma_i}{2}$$

T_i was the temperature at i, in K; D was the diameter of pipeline, in m; ρ_i was the density at i, in kg m^{-3}; L was the distance from the starting point to the center of the leakage site, in m; u_i was the speed at i, in m sec^{-1}; A_c was the sectional area of the pipeline, in m^2; $M_{ai} = u_i/C$ the Mach number at i, i.e., the ratio of the air flowing speed at i and the local sound speed without dimension; A_{or} was the area of the leakage hole, in m^2; Q_v was the volume quantity, in m^3 h^{-1}; R_e was the Reynolds number; M was the molecular weight, in kg $kmol^{-1}$; $f = 0.0232\ R_e^{-0.1507}$, f was the friction factor; The gas leakage rate in different leakage equivalent diameter was calculated based on the above model.

NUMERICAL SIMULATION ANALYSIS IN DIFFERENT LEAKAGE CONDITIONS

The main setting parameter of the gas-liquid linkage valve is the pressure lowering rate. Different leakage conditions have different impacts on the pressure changing rate in the starting valve of the pipe, as a result, it is necessary to make analysis from different aspects including leakage site, pipe diameter, transportation quantity, the operating pressure of the pipeline and so on. The variation span for those parameters are as follows: Pipe diameter: 426~914 mm; transportation quantity: 1500~15000 thousand cube day^{-1}; operating pressure: 2~6 MPa; leakage equivalent diameter: 50~200 mm.

Firstly, how different leakage locations influenced the pressure of the starting valve was analyzed. One leakage point was set every 4 km between the starting and the finishing valve. According to the change of the pressure in the starting valve after the dynamic simulation leakage points were set, the effect of different locations on the pressure in the starting valve was analyzed. The simulation pipe diameter was 426 mm, the length of the pipeline was 32 km, the pressure in the starting valve was 2 Mpa, the transportation quantity was 1500 thousand cube day^{-1}. Through simulation, the changing curve between the pressure lowering rate of the starting valve and the leakage points was as follows (Fig. 1). According to Table 1, the father the leakage point was from the starting valve, the smaller the pressure lowering rate was. In addition, the maximum pressure lowering rate had delays to time to some extent.

Table 1: Value of constants in the fitting formular

a	$1.49640519654899\times10^{-4}$
b	$-1.71841065567175\times10^{-2}$
c	$-6.54093031537799\times10^{-5}$
d	$3.50039139913048\times10^{-3}$
e	$2.7523837274249\times10^{-2}$

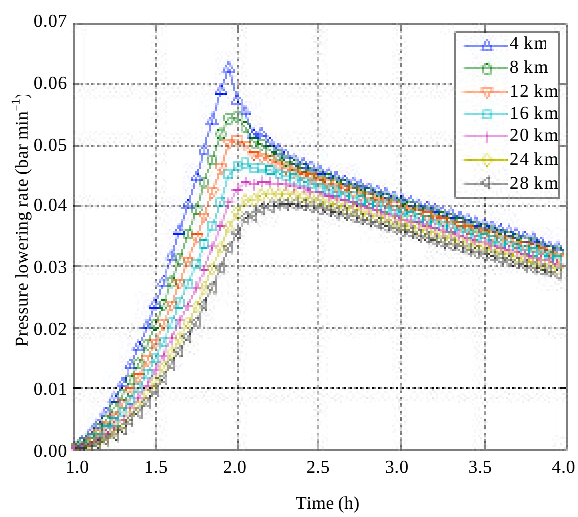

Fig. 1: Pressure lowering rate of the starting valve in different leakage points

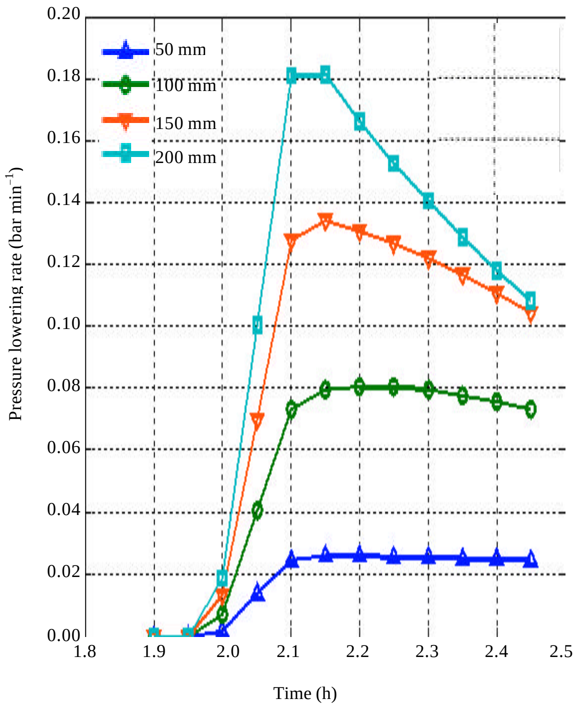

Fig. 2: Pressure lowering rate of the starting valve at different equivalent diameters

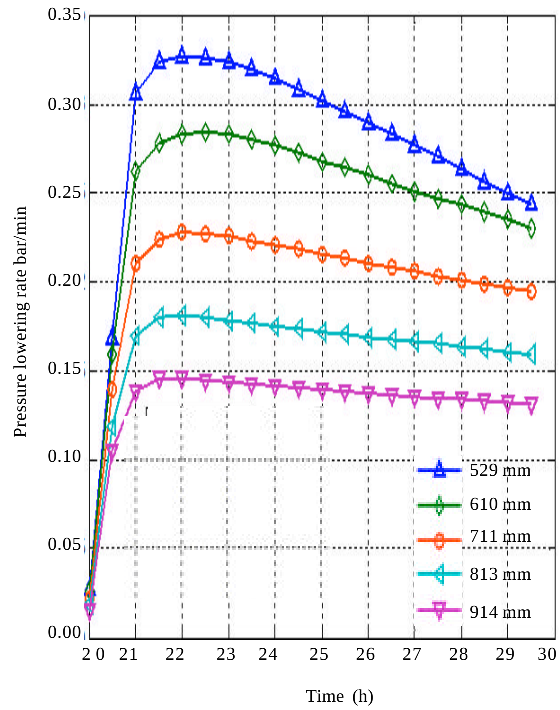

Fig. 3: Pressure lowering rate of the starting valve at different diameters

Secondly, how different leakage equivalent diameters affected the lowering rate in the starting valve is analyzed. When the transportation quantity is 1500 thousand cube day^{-1}, we took the starting pressure as 2 MPa, the pipe diameter as 426 mm, the distance from the leakage point to the starting point as 16 km and supposed the leakage happen at 1.9 h, the leakage point form at 0.1 h, the background pressure be the atmosphere. Then the operating conditions in 5 h were simulated based on different leakage equivalent diameter (50, 100, 150 and 200 mm). Finally, we got the pressure lowering curve in the starting valve when leakages happened in different equivalent diameters, as follows (Fig. 2).

With the transportation quantity, the pressure at the starting valve and the pipe diameter unchanged, the pressure lowering rate at the starting valve rapidly increased with the increasing of the equivalent diameter. According to Fig. 2, the leakage rate reached the peak value after 7 min when the leakage equivalent diameter kept unchanged and then lowered to a steady value which needed more time in case of larger pipe diameter and vice verse. The pipe storage quantity would be more if there was more diameter under the same pressure and as a result, there would have more buffer space for leakage transient conditions.

Next, the effect of different pipe diameters on the pressure lowering rate at the starting valve was analyzed. When the transportation quantity was 7500 cube day^{-1}, the starting pressure was 6 MPa and the leakage equivalent diameter was 100 mm, the pressure lowering rate of the starting valve for different diameters was as follows (Fig. 3) (diameters: 529, 610, 711, 813 and 914 mm).

With the transportation quantity, the starting pressure and the equivalent diameter at the leakage point unchanged, the pressure lowering rate in the starting valve began to increase from the happening of the leakage till 2.2 h (i.e., 12 min after the leakage happened) when it reached the peak value. The pressure lowering rate declined with the increasing of the diameter.

Finally, the author made an analysis about the effect of transportation on the pressure of the starting valve when the leakage happened. Several parameters were taken as follows: The pressure of the starting valve: 6 MPa; the leakage equivalent diameter: 100 mm; the diameter: 813 mm. For different transportation volumes (1500~1200 cube day^{-1}), the pressure lowering rate of the starting valve was as follows (Fig. 4). From Fig. 4, we could know that the transportation quantity did not affect the pressure lowering rate much in case of leakage.

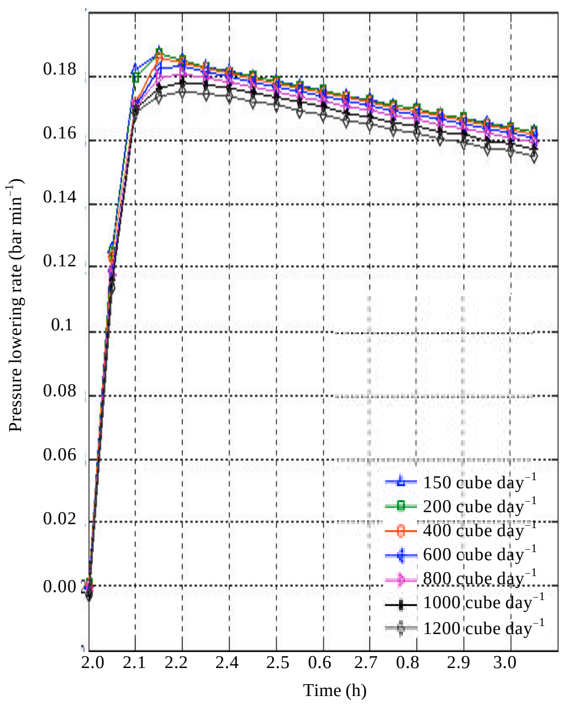

Fig. 4: Pressure lowering rate of the starting valve for different transportation quantity

MULTIPLE FITTING OF SIMULATION DATA

To obtain the quantitative relation between the pressure, its lowering rate of the starting valve and different parameters such as transportation quantity, pressure, diameter and leakage equipvalent diameter and correctly set the key parameter of gas-liquid linkage valve, multiple fitting was needed for all the original data calculated through simulation thus obtaining a fitting formular which could estimate the maximum lowering rate. Multiple linear regression model was established as Eq. 5:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_p X_p + \varepsilon \quad (5)$$

n times of experiments were conducted for variables to obtain the following linear model:

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1p} \\ 1 & x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{np} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix} \quad (6)$$

The least square method was used to calculate b_0, b_1, b_2, b_n and then sum of squares of deviations were calculated:

$$Q = \sum_{i=1}^{n} \left(y_i - \beta_0 - \beta_1 x_{i1} - ..- \beta_p x_{ip} \right)^2 \quad (7)$$

The normal equation was got by the mimimum Q:

$$\begin{pmatrix} n & \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i2} & \cdots & \sum_{i=1}^{n} x_{ip} \\ \sum_{i=1}^{n} x_{i1} & \sum_{i=1}^{n} x_{i1}^2 & \sum_{i=1}^{n} x_{i1}x_{i2} & \cdots & \sum_{i=1}^{n} x_{i1}x_{ip} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sum_{i=1}^{n} x_{ip} & \sum_{i=1}^{n} x_{ip}x_{i1} & \sum_{i=1}^{n} x_{ip}x_{i1} & \cdots & \sum_{i=1}^{n} x_{ip}^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_p \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_{i1}y_i \\ \vdots \\ \sum_{i=1}^{n} x_{ip}y_i \end{pmatrix} \quad (8)$$

The pressure lowering rate in different conditions got by simulation, respectively put into Eq. 8 to calculate the coefficient matrix and the constant variables, thus calculating the coefficients of each independent variables and obtaining the multiple linear fitting equation (Wang and Zhu, 2007):

$$V_{max} = aQ + bP + cD + dD_L + e \quad (9)$$

where, V_{max} was the highest lowering rate of the pressure in the starting valve, in bar/min; Q was the transportation quantity, in million cube/day; P was the normal pressure of the pipeline, in MPa; D was the diameter of the pipe, in mm; D_L was the equivalent diameter in the leakage site, in mm. The value of each constant in the fitting formular was as follows.

According to Eq. 9, given the diameter, pressure, transportation quantity and the leakage equivalent diameter, we could calculate the highest lowering rate of the pressure in the starting valve, thus providing a theoretical support for the parameter setting of the gas-liquid linkage valve. Through fitting of the simulation data, a comparison between the simulation data and the highest lowering rate in the starting valve was obtained as Fig. 5.

From Fig. 5, we know that the fitting formular could make estimation relative correctly in larger diameter, higher pressure and larger leakage equipvalent diameter (over 100 mm) while there were large differences in smaller diameter, lower pressure and smaller leakage equipvalent diameter (less than 50 mm) due to low sensetivity to each independent variable caused by slower change of

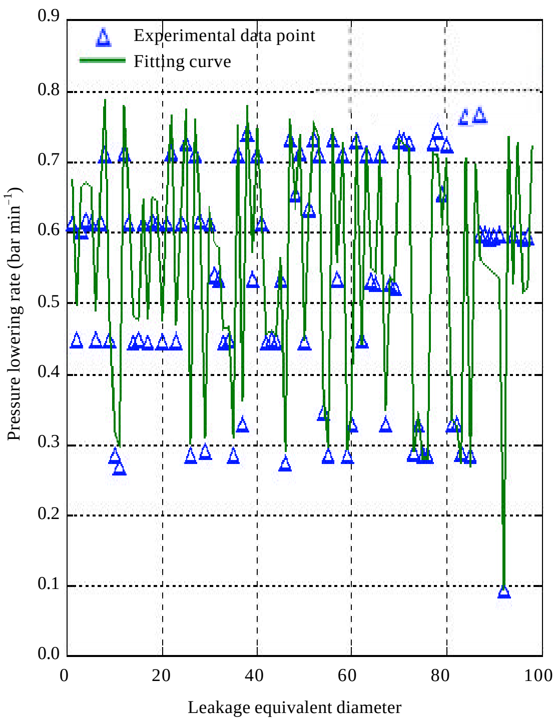

Fig. 5: Comparison between fitting value and the experimental data

pressure lowering rate. However, the accuracy was generally over 85% which could be a base to analyze the pipeline leakage on site.

CONCLUSION

Through multiple fitting on the data of the numerical simulation experiment, an analytical formula was obtained by which the highest pressure lowering rate could be estimated with known transportation quantity, diameter, pressure and leakage equivalent diameter. The average calculation error was less than 10%. Subsequently, this formula could be a theoretical guidance for the parameter setting of the gas-liquid linkage valve and had profound guiding significance for the diagnosis of leakage.

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