Parametric Identification of Ruptures in Gas Pipelines

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Abstract. The paper solves the problem of predicting the emergency states of gas pipelines in cases where the initial parameters of the pipeline are not fully known a priori and can change during operation. The coefficient of heat transfer from gas to the external medium and the coefficient of internal viscous friction of hydraulic resistance are considered as such parameters. The theoretical calculation of these coefficients with sufficient accuracy for practice is very difficult due to the significant uncertainty of the actual conditions of heat transfer along the route and the current state of the pipeline. To solve this problem, a mathematical model of a steady gas flow in a pipeline is proposed, which is based on the assumptions about the polytrophic nature of the gas, as well as the non-isentropic and nonadiabatic nature of its flow. Together with the model, a method for identifying undefined coefficients has been developed. The problem of building the corresponding computational procedures with unknown boundary conditions is solved. An analysis of emergency states of a gas pipeline for cases of complete rupture and partial destruction of its wall was carried out by means of numerical modeling. Examples of using the developed model for predicting emergency states of gas pipelines are given.

1. Introduction

Emergency conditions of gas pipelines are the subject of intensive research due to the catastrophic consequences of these conditions for the environment [1-7]. A common option of the occurrence of emergency outflows in gas main pipelines is local destruction of the pipeline wall, which occurs as a result of its corrosion, mechanical damage or deformation [8]. The appearance of such damage even at the initial stages of wall destruction can be detected by changes in the state of the gas and its flow rate both at the beginning and at the end of the considered section of the gas pipeline. Since these changes are related to the area of destruction of the pipeline and the location of the leak on the track line, it is legitimate to formulate the problem: by the known changes in the state of gas and its flow at the controlled boundaries of the pipeline, determine (identify) the area of local destruction and its location relative to the indicated boundaries. At the same time, it is assumed that the solution of this problem by installing the corresponding sensors along the entire pipeline, including on its hard-to-reach sections, is economically inexpedient.
2. State of the problem
Most of the research on emergency gas pipeline ruptures is devoted to the actual process of gas outflow through the rupture [9-14]. In [11], when analyzing the process of gas outflow, the influence of the state of the atmosphere is additionally considered. The article [14] considers the case of complete destruction of a gas pipeline. However, the outflow models used in these works are autonomous and are not included in the general system of equations describing the process of gas transportation through the pipeline.

The closest to the topic of this research work [15] is devoted to the determination of the parameters of the main pipeline rupture using a simple model based on the pressure values at the ends of the emergency section. This paper proposes a method for identifying leakage parameters based on a complete thermodynamic model of gas movement in a pipeline. The use of the full model makes it possible to obtain information about all the characteristics of the gas along the entire length of the section and, as a result, increase the identification accuracy. This approach meets modern requirements for early detection of local leaks in a gas pipeline and remote determination of the parameters of its rupture [16-22].

From a practical point of view, the development of an additional identification method meets the concept of multi-alternative, which is in demand, first of all, in critical facilities [23-25].

3. Mathematical model of a gas transportation system
Before notation:

- $P_1$, $P_2$, $P_3$, $P_4$ – absolute gas pressures at the beginning of the pipeline, in the place of its damage, in the outlet section of the rupture and at the end of the pipeline, Pa;
- $T_2$, $T_{a2}$, $T_1$, $T(\alpha)$, $T_{amb}$ – thermodynamic gas temperature: at the end of the section; at point $\alpha$ of pipeline rupture; in the outer section of the rupture; current temperature at a distance of $\alpha$ meters from a certain reference point; average ambient temperature along the length of the section, K, respectively;
- $w_1$, $w_{a2}$, $w_2$ – gas velocity in the above mentioned sections of the pipeline and at the end of the section, m/s;
- $g$ – acceleration of gravity, m/s$^2$;
- $h_1$, $h_{a2}$, $h_2$ – leveling levels of the beginning of the pipeline, the place of rupture and the end of the pipeline, m;
- $D$ – inner diameter of the pipeline, m;
- $S$, $S_a$ – internal cross-sectional area of the pipeline and the destroyed part of the wall, m$^2$;
- $L$ – pipeline length along its geometric axis, m;
- $L_a$ – distance from the beginning of the pipeline to the point of rupture, m; $L_a=\alpha L$, $\alpha=[0;1]$;
- $Q_1$, $Q_2$, $Q$ – gas consumption at the beginning of the pipeline, through the rupture section, and at the end of the pipeline, kg/s; $Q=Q+Q_2$;
- $C_p$ – molar heat capacity of gas at constant pressure, J/(mol-K);
- $C_f$ – heat transfer coefficient from gas to external environment, J/(s·m$^2$·K);
- $\nu_1$, $\nu_a$, $\nu_2$ – molar gas flow rates in the corresponding sections, mol/s, determined from the expressions:

$$\nu_1 = \frac{\rho_1 w_1 S}{\mu}, \quad \nu_a = \frac{\rho_a w_a S}{\mu}, \quad \ldots, \quad \nu_2 = \frac{\rho_2 w_2 S}{\mu},$$

where $\rho_1$, $\rho_a$, $\rho_2$, $\rho_3$ – gas density in the considered sections, kg/m$^3$; $\mu$ – molar mass of gas, kg/mol;

$$\rho_1 = \frac{\mu}{V_{\mu1}}, \quad \rho_a = \frac{\mu}{V_{\mu a}}, \quad \ldots, \quad \rho_2 = \frac{\mu}{V_{\mu2}},$$

$V_{\mu1}$, $V_{\mu a}$, ..., $V_{\mu2}$ – molar volumes, m$^3$/mol;

$$V_{\mu1} = \frac{P_1 T_1}{\mu \rho_1 T_{amb}} \quad V_{\mu2} = \frac{P_2 T_2}{\mu \rho_2 T_{amb}} \quad V_{\mu a} = \frac{P_a T_a}{\mu \rho_a T_{amb}},$$

$V_{\mu a}$ – molar volume of gas at temperature $T_a = 273$ K and pressure $P_a = 1.01 \times 10^5$ Pa, m$^3$/mol;
\(\gamma\) – adiabatic exponent; \(R\) – universal gas constant, J/(mol·K);
\(\beta\) – current angle of inclination of the pipeline axis to the horizon, rad;
\(\lambda\) – internal viscous friction coefficient in gas flow.

Taking into account the accepted designations, let us describe the process of gas transportation and its outflow through the rupture by relations reflecting the laws of conservation of mass, momentum and energy [26-30]:

1) Conditions for the continuity of the gas flow in all sections of the pipeline:

\[
\rho_1 w_1 S = \rho_{a} w_{a} S;
\rho_{a} w_{a} S = \rho_{w} S + \rho_{2} w_{2} S;
\rho_{2} w_{2} S = Q.
\]

2) Equations characterizing the change in the amount of gas movement along the pipeline:

\[
\rho_1 w_1 S (w_a - w_1) = (P_1 - P_a) S - \lambda \frac{\rho_1 w_1 S}{2D} \int_0^h \sin\beta(h) dh;
\rho_2 w_2 S (w_2 - w_a) = (P_a - P_2) S - \lambda \frac{\rho_2 w_2 S}{2D} \int_0^h \sin\beta(h) dh.
\]

3) Heat capacity equations for molar rate:

\[
\left(C_p T_a + \frac{\mu w_a^2}{2} + \mu g h_a\right) v_a = \left(C_p T_a + \frac{\mu w_a^2}{2} + \mu g h_a\right) v_a + \frac{\pi D\mu}{\rho_1 w_1 S} \int_0^L (T(x) - T_{amb}) dx
\]

4) Equations describing the adiabatic process of gas outflow through the discontinuity with the local speed of sound:

\[
w_r^2 = \frac{\gamma R T_r}{\mu},
\]

\[
T_r = \left(\frac{P_r}{P_a}\right)^{\gamma-1}\]

\[
P_r = \left(\frac{2}{\gamma+1}\right)\gamma
\]

The obtained relations are unsolvable in an analytical form with respect to any of the thermodynamic quantities involved in them, and a transition to numerical methods of solution is necessary.
4. Difference modeling
A numerical study of model (1)-(10) is possible by using a difference solution scheme that allows, with a certain step \( st \), calculating the pressure, velocity and temperature of the gas in any section of the pipeline:

\[
h_{i+1} = h_i + st \cdot \sin \beta; \quad i = 0, 1, ..., 1/st; \tag{11}\]
\[
\rho_i w_i S = \rho_{i+1} w_{i+1} S; \tag{12}\]
\[
\rho_0 w_0 S = \rho_r w_r S + \rho_{al/st} w_{al/st} S; \tag{13}\]
\[
\rho_{al/st} w_{al/st} S = Q; \tag{14}\]
\[
\rho_i w_i (w_{i+1} - w_i) = (P_i - P_{i+1}) S - \frac{\rho_i w_i S}{2D} \left( \frac{w_i + w_{i+1}}{2} \right) \cdot st \cdot L -
\]
\[
g \rho_i w_i \left( \frac{w_i + w_{i+1}}{2} \right) \cdot st \cdot L \sin \beta; \quad \ldots \tag{15}\]
\[
C_p T_{i+1} + \frac{\mu w_i^2}{2} + \mu g h_{i+1} = C_p T_{i+2} + \frac{\mu w_i^2}{2} + \mu g h_{i+2} + C_T \frac{\pi D \mu}{\rho_{al/st} w_{i+1} S} \left( \frac{T_{i+1} + T_{i+2}}{2} - T_{amb} \right) \cdot st \cdot L; \tag{16}\]
\[
\ldots
\]
\[
C_p T_{al/st} + \frac{\mu w_i^2}{2} + \mu g h_{al/st} =
\]
\[
= C_p T_a + \frac{\mu w_i^2}{2} + \mu g h_a + C_T \frac{\pi D \mu}{\rho_{al/st} w_{al/st} S} \left( \frac{T_{al/st} + T_a}{2} - T_{amb} \right) \cdot st \cdot L; \tag{17}\]
\[
\left( C_p T_a + \frac{\mu w_i^2}{2} + \mu g h_a \right) \nu_a = \left( C_p T_r + \frac{\mu w_i^2}{2} + \mu g h_a \right) \nu_r + \left( C_p T_{al/st} + \frac{\mu w_i^2}{2} + \mu g h_{al/st} \right) +
\]
\[
\ldots \tag{18}\]
\[
+ C_T \frac{\pi D \mu}{\rho_{al/st} w_{al/st} S} \left( \frac{T_{al/st} + T_{al/st}}{2} - T_{amb} \right) \cdot st \cdot L \right) \nu_{al/st};
\]
\[
\left( C_p T_{al/st} + \frac{\mu w_i^2}{2} + \mu g h_{al/st} \right) =
\]
\[
+ C_p T_{al/st} + \frac{\mu w_i^2}{2} + \mu g h_{al/st} + C_T \frac{\pi D \mu}{\rho_{al/st} w_{al/st} S} \left( \frac{T_{al/st} + T_{al/st}}{2} - T_{amb} \right) \cdot st \cdot L; \tag{19}\]
\[
\ldots
\]
\[
\nu_r = \frac{\gamma RT_r}{\mu}; \quad T_r = \left( \frac{P_r}{P_0} \right)^{\frac{\gamma-1}{\gamma}}; \quad \frac{P_r}{P_\alpha} = \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}}. \tag{20}\]

The total number of equations for the numerical simulation of the transportation process under consideration is determined by the number of nodes in the computational grid. If the design scheme contains \( n \) nodes, one of which coincides with the rupture point, then it is necessary to have three
equations for each elementary line segment: one equation from (1), (3), one equation from (4), (5), and one equation from (6), (7). In addition, it is necessary to add conditions (2),(8)-(10) for the outflow point. Thus, the total number of equations is \(3(n-1)+4 = 3n+1\), in particular, for \(n=15\) we obtain a system of 46 equations.

5. Practical example
For a quantitative analysis of the interrelationships of the gas thermodynamic parameters of interest and the choice of numerical methods for solving the posed problem of identifying these parameters, we will use the example of a gas pipeline with the following characteristics: \(T_1 = 310\) K; \(T_2 = 290\) K; \(T_{amb} = 285\) K; \(P_1 = 220\times10^5\) Pa; \(P_2 = 147\times10^5\) Pa; \(w_1 = 5\) m/s; \(w_2 = 7\) m/s; \(C_f = 1.115\) J/(s·m²·K); \(\lambda = 0.00672\); \(\beta = 0\); \(L = 300\times10^3\) m; \(S = 0.234\) m²; \(D = 0.546\) m; \(g = 9.81\) m/s²; \(C_p = 35.6\) J/(mol·K); \(C_v = 27.3\) J/(mol·K); \(R = 8.31\) J/(mol·K); \(\mu = 16.04\times10^{-3}\) kg/mol; \(V_{m,n} = 22.4\times10^{-3}\) m³/mol; \(Q = \rho_1 w_1 S = 160.711\) kg/s; \(S_r = 2.74\times10^{-3}\) m² = 27.4 cm²; \(\alpha = 0.62\).

The solution of system (1)-(10) using the difference scheme given in step 3 is shown graphically in figure 1 for the main quantities characterizing the state of the gas: pressure \(P\), temperature \(T\) and velocity \(w\), changing along the line in two modes - normal and emergency: with the outflow from the rupture at the point with the value \(\alpha=0.62\), the rupture area \(S_r = 2.74\times10^{-3}\) m² and flow rate \(Q = 60\) kg/s.

![Figure 1](image1.png)

**Figure 1.** Comparative characteristics of gas during normal operation (norm) and with a rupture (em) at the point \(\alpha=0.62\), the rupture area \(S_r = 2.74\times10^{-3}\) m²

![Figure 2](image2.png)

**Figure 2.** Lines of equal level of surfaces \(P_2(S_r,\alpha)\), \(Q_2(S_r,\alpha)\). With indication of the parameters of the rupture for \(Q_r = 60\) kg/s, \(P_2 = 8\) MPa

The nature of the change in \(P\), \(T\) and \(w\) in figure 1 indicates that the pressure \(P_2\) at the outlet end of the line is most sensitive to gas leakage. In addition, gas flow rates at both ends of the main line \(Q\) and \(Q_r\) are available for monitoring, which implies the possibility of determining the emergency flow rate as \(Q_r = Q_1 - Q\). As a result, the pressure \(P_2\) at the outlet of the main line and the emergency flow rate \(Q_r\) were chosen as the initial controlled values used to identify the location of the rupture \(\alpha\) and its area \(S_r\).

Figure 2 shows lines of equal level of surfaces \(P_2(S_r,\alpha)\) and \(Q_2(S_r,\alpha)\). The location of these lines testifies to the one-to-one correspondence of any pair of monitored quantities \((P_2,Q_r)\) to the required pair of rupture parameters \((S_r,\alpha)\).

This circumstance opens up the possibility of formulating the problem of parametric identification as a problem of directed search for unknowns \((S_r,\alpha)\) ensuring the possibility of simultaneous fulfillment of two equalities: \(P_2(S_r,\alpha) = P_{2,act}\) and \(Q_2(S_r,\alpha) = Q_{r,act}\), where \(P_{2,act}\) and \(Q_{r,act}\) are the actual current values of the pressure at the outlet of the main pipeline and emergency flow recorded by the sensors.

To solve this problem, the coordinate search method and the gradient motion method were used.
Coordinate search procedures:
1) An arbitrary starting point of the search is selected \((S_{r,0}, \alpha_0)\).
2) Using any one-dimensional search method (in the example, the golden section method was used), the search is made for the minimum of the disparity \(E_P\) of the calculated \(P_2\) and the actual values \(P_{2,\text{act}}\) along the \(S_r\) coordinate:

\[
E_P(S_r, \alpha) = 
\sqrt{1 - \frac{P_2(S_r, \alpha)}{P_{2,\text{act}}}} \to \min ,
\]  \hfill (21)

defined at some point \((S_{r,1}, \alpha_0)\), figure 3.
3) From the point \((S_{r,1}, \alpha_0)\), the minimum of the disparity \(E_Q\) of the calculated \(Q_r\) and actual values \(Q_{r,\text{act}}\) is sought along the coordinate \(\alpha\):

\[
E_Q(S_r, \alpha) = 
\sqrt{1 - \frac{Q_r(S_r, \alpha)}{Q_{r,\text{act}}}} \to \min ,
\]  \hfill (22)

defined at the point \((S_{r,1}, \alpha_1)\).
4) The search is repeated from step 2 until each disparity reaches a given small value \(\varepsilon\).

A graphical illustration of the coordinate search for a solution is shown in figure 3.
To complete the search with disparity values not exceeding \(\varepsilon=6 \times 10^{-5}\), it took 10 search cycles (the last point \((S_{r,10}, \alpha_{10})\).

![Figure 3](image)

**Figure 3.** Parameter identification by coordinate search. Starting point \((0.35; 2.5 \times 10^{-5})\).

![Figure 4](image)

**Figure 4.** Parameter identification by gradient search. Starting point \((0.35; 2.5 \times 10^{-5})\).

Algorithm of the gradient method for finding a solution:
1) An arbitrary starting point of the search is selected \((S_{r,0}, \alpha_0)\).
2) The disparity gradient is determined numerically:

\[
\nabla E_P \approx \begin{bmatrix} \frac{\Delta E_{P,S}}{\Delta S_r} & \frac{\Delta E_{P,\alpha}}{\Delta \alpha} \end{bmatrix} ,
\]  \hfill (23)
where \( \Delta E_{P,S} \) – increment of the disparity \( E_P(S_r, \alpha) \) of the calculated \( P_2 \) and actual \( P_{2,act} \) values along the coordinate \( S_r \), defined in the vicinity of the point \( (S_{r,0}, \alpha_0) \); \( \Delta E_{P,\alpha} \) – increment of the disparity \( E_P(S_r, \alpha) \) along the coordinate \( \alpha \), defined in the vicinity of the point \( (S_{r,0}, \alpha_0) \).

3) In the direction of the gradient, the one-dimensional search method is used to search for the minimum of the disparity:

\[
E_P(S_r, \alpha) = \sqrt{\left(1 - \frac{P_2(S_r, \alpha)}{P_{2,\text{act}}}\right)^2} \rightarrow \text{min},
\]

defined at the point \( (S_{r,1}, \alpha_1) \). And the component of the gradient along the variable \( \alpha \) is multiplied by the scaling factor \( \alpha_0/S_{r,0} \).

4) The search is repeated from step 2 along the gradient of the disparity:

\[
\nabla E_Q \approx \left[ \frac{\Delta E_{Q,S}}{\Delta S_r}, S_{r,0} \frac{\Delta E_{Q,\alpha}}{\Delta \alpha}, \alpha_0 \right]^T,
\]

defined similarly to \( \nabla E_P \), and so on, until each discrepancy reaches a small value \( \epsilon \).

An illustration of the search for a solution by the gradient method is shown in figure 4.

6. Conclusions
The problem of promptly determining the parameters of emergency gas pipeline ruptures can be successfully solved on the basis of analytical models of gas flow rate, pressure and velocity along the entire controlled section of the gas pipeline.

The use of difference methods of analysis of these models opens up the possibility of remote and automatic assessment of the state of gas at any point of the pipeline in real time.

The developed procedures for identifying the parameters of emergency outflows have confirmed their efficiency during experimental verification.

The proposed identification method meets the current trend of automation of monitoring and control of gas transportation in rapidly changing conditions of gas pipelines operation.

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