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A Refined Algorithm for Leak Location in Gas Pipelines with Determination of Quantitative Parameters

Aigul T. Bakesheva[1], Vadim G. Fetisov[2] and Vladimir V. Pshenin[2]

[1]*PhD student, Satbayev University, Almaty, Republic of Kazakhstan*
[2]*PhD in Engineering, Department of Transport and Storage of Oil and Gas, Saint Petersburg Mining University, Saint Petersburg, Russia*

Abstract

One of the most important problems of pipeline transport is maintaining a healthy state of the linear part of field and trunk pipelines. Numerous surveys show that underground pipelines operating for several decades are susceptible to aging processes caused by corrosion and mechanical damage to the pipeline, which result in gas leakage. A large amount of natural gas is lost from through defects in main gas pipelines annually, which leads to environmental pollution, emergency situations, gas shortages to consumers, and penalties. The studies presented in this article address the main issues associated with determining the location and size of leaks in gas pipelines. The main methods for detecting leaks are described, and a refined algorithm is proposed with the quantification of the occurrence of leaks in the pipeline.

Keywords: Natural Gas Transport, Gas Leaks, Gas Pipelines, Gas Contamination

I. INTRODUCTION

In order to ensure efficient and safe operation of main gas pipelines, one should solve the problems of the timely detection and elimination of leaks as well as determine the magnitude of natural gas losses [1].

The most difficult case is leakage from underground gas pipelines, since the filtration of gas in the ground, its distribution from the leakage spot, and accumulation in underground voids are determined by a large number of factors.

Damage to underground gas pipelines is caused by the following reasons: mechanical impacts during excavation works as a result of deviations from safety rules and work procedures; corrosion destruction of pipe metal as a result of violations during construction and/or inadequate control of technical conditions; disconnection and opening of pipeline joints due to poor-quality construction and installation works [2].

Natural gas leaks, in addition to its losses, may result in damage to buildings and structures, injuries and death of people due to the combustion or explosion of a gas-air mixture, financial and economic costs due to gas shortages to consumers and penalties [3, 4].

There are two categories of pipeline leak detection methods: continuous and periodic monitoring methods.

According to Kurakina, Radchenko and Yufin (1976), the linearization of the equations of unsteady fluid motion in pipelines presents a significant error in determining the pressure [5]. The distinctive features of the method proposed in this work consist in the fact that a nonlinear model is used to determine hydraulic characteristics (pressure and flow rate). The algorithm used by the authors makes it possible to use any amount of pressure measurement data, and in a non-stationary case, flow rate.

II. PROBLEM FORMULATION

The calculated pressure values are determined by hydraulic calculation of the main pipeline. Hydraulic calculation should be performed according to the models of steady and unsteady gas flow regimes. The advantage of the models of unsteady gas flow is that it is possible to track the change in the pressure on pipeline valves over time. The difficulties that arise during this process include determining the location of cracks or holes.

The advantage of the models of steady gas flow consists in the simplicity of calculations and the determination of damage sites. The disadvantage is as follows: in order to fix the steady gas flow regime after a pressure drop in the gas pipeline, a period of time is required at which gas losses can be calculated.

III. MATERIALS AND METHODS

In order to simulate one-dimensional linear filtration of a continuous medium into the ground, the Darcy equation is used [6, 7]. The second classical equation, expressing the principle of mass conservation during the motion of a continuous medium in the ground, is the continuity equation. In this equation, a leak source with intensity q is considered as a local source that can be described using the Dirac function [8]. As a result, the mathematical model has the following form:

$$\frac{\partial \omega}{\partial t} = \epsilon \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) - \epsilon \frac{q}{F} \delta(x - x_g) \delta(y - y_g), \qquad (1)$$

where ω is the filtration rate as a function of time t and spatial Cartesian coordinates x, y; ϵ is the ground conductivity coefficient.

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Based on theoretical studies, it was found that the general formation process of a gas contamination region could be divided into two non-stationary phases. The first phase starts from the moment a leak occurs and ends when the gas reaches the ground surface. The filtration rate on the ground surface over the entire period is zero. The second non-stationary filtration phase starts from the moment the gas reaches the ground surface and ends with the transition to a stationary process of gas leakage through the ground into the atmosphere (Fig. 1).

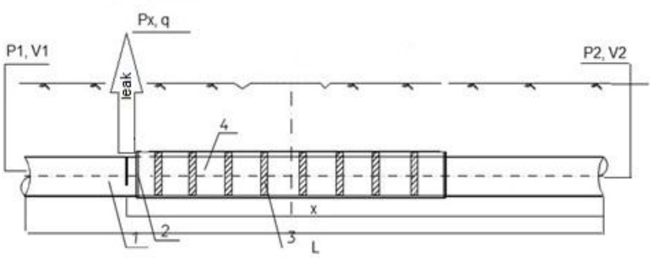

Fig. 1. Leaky gas pipeline

1 – a gas pipeline; 2 – a rubber collar; 3 – a spacer; 4 – a protective casing; P_1, P_2 are the initial and final pressure values in the gas pipeline; P_x is the pressure in the leakage zone; q is the leak; V_1, V_2 are the volumetric gas flow rates at the beginning and end of the pipeline; x is the distance from the leak; L is the total length of the gas pipeline.

III.I Theoretical Research

When selecting the initial and boundary conditions for the first phase, it was considered that at the initial time there is no gas filtration in the ground, the ground surface for gas is impenetrable, and the source of the filtration rate is zero

$$\omega(x, y, 0) = 0;\ \omega(0, h, t) = 0;\ \omega(\infty, h, t) = 0, \tag{2}$$

where h is the depth of the gas pipeline in the ground.

In theoretical research, the problem was solved using the integral transformation of the Fourier equation

$$\omega = \frac{q}{2\pi F}\int_0^\infty \frac{\sin\lambda y_g \sin\lambda y}{\lambda}\Big\{\left[\mathrm{y}\left(x - x_g\right) - 1\right]\left[e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} - \lambda\sqrt{\epsilon t}\right) - e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} + \lambda\sqrt{\epsilon t}\right)\right] - \sigma(x - x_g)\left[e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} - \lambda\sqrt{\epsilon t}\right) - e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} + \lambda\sqrt{\epsilon t}\right)\right]\Big\} d\lambda, \tag{3}$$

where $\sigma\left(x - x_g\right)$ is the Heaviside step function.

In order to determine the patterns of the frequency field of the gas filtration rate in the ground, an analytical calculation was performed based on the created mathematical model of the algorithm.

In the event of small gas leakage from the gas pipeline, an indication on the ground surface is possible after 5-10 minutes, depending on the characteristics of the ground [9]. The gas contamination region due to leakage from the gas pipeline occupies an area comparable to the size of a trench, the axis of which is directed along the axis of the gas pipeline [10, 11].

For the non-stationary phase of occurrence of the gas contamination region, one should evaluate the nature of the end of formation of the leakage zone and the amount of gas leakage into the atmosphere [12-14]. Suppose that by the leakage beginning *(t=0)*, the gas pipeline is deployed in a stationary mode, and the pressure due to the shallow location of the gas pipeline over the entire area is $P(x,y,0) = P_a$.

The algorithm with the given initial and boundary conditions is solved by the method of integral transformations through the Fourier equation with the changed y and the transformation of the Laplace equation in time t.

$$P(x, y, t) = P_a + \frac{q}{2\pi F}\int_0^\infty \frac{\sin\lambda y_g \sin\lambda y}{\lambda}\Big\{\left[\sigma\left(x - x_g\right) - 1\right]\left[e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} - \lambda\sqrt{\epsilon t}\right) - e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} + \lambda\sqrt{\epsilon t}\right)\right] - \sigma(x - x_g)\left[e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} - \lambda\sqrt{\epsilon t}\right) - e^{-\lambda(x_g - x)} erfc\left(\frac{x_g - x}{2\sqrt{\epsilon t}} + \lambda\sqrt{\epsilon t}\right)\right]\Big\} d\lambda, \tag{4}$$

In order to determine the gas filtration rate in the ground as a function of spatial time coordinates, the Darcy equation for porous media is used

$$\omega(x, y, t) = \frac{k}{2}\left(\frac{\partial P}{\partial x} + \frac{\partial P}{\partial y}\right). \tag{5}$$

In equation (5), the pressure gradient is found using a differential equation with a linear coordinate.

IV. RESULTS AND DISCUSSION

Based on the research results, with regard to the implementation of the mathematical model and algorithm, a graph was constructed that limits the boundary of the gas contamination region for the first and second phases of the non-stationary gas filtration process (Fig. 2). This graph shows the direction of the gas contamination region along the pipeline.

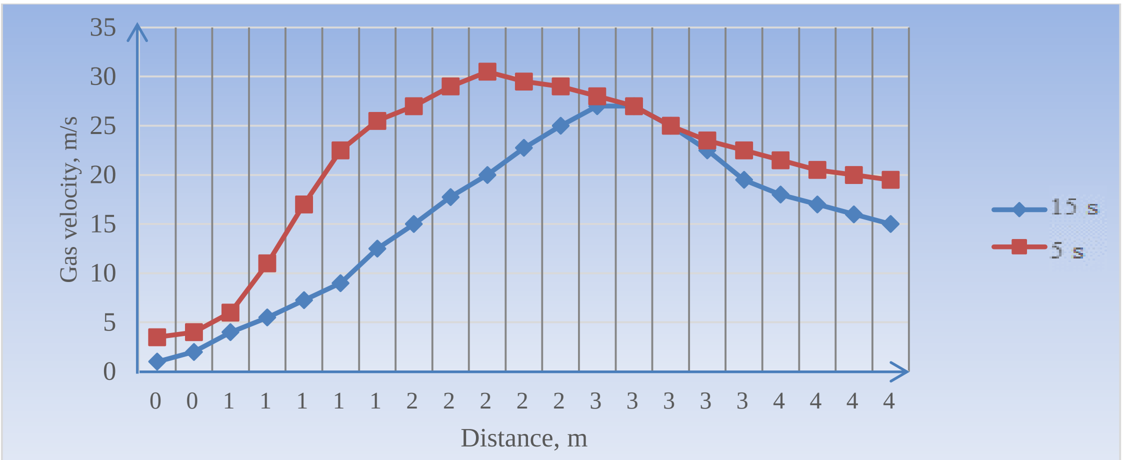

Fig. 2. Gas contamination regions along the pipeline

V. CONCLUSIONS

An analysis of the research results shows that the largest volume of gas contamination occurs at the end of the first phase of non-stationary gas filtration into the ground. This is due to the presence of a certain resistance in the ground during the period when the gas reaches the surface. As the gas reaches the surface, the filtration resistance decreases, which results in the formation of a gas contamination region. After the gas reaches the ground surface, the filtration resistance decreases sharply, which leads to an increase in the rate of gas leakage from the ground into the atmosphere. The area of the gas contamination surface should decrease, and the rate of gas leakage into the atmosphere will increase, based on the continuity equation.

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