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Investigation of Changes in Natural Gas Parameters along a Damaged Gas Pipeline

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Abstract

The paper presents a mathematical model of the stationary flow of natural gas in an inclined gas pipeline, which makes it possible to calculate the gas parameters (pressure, temperature, compressibility factor) in every cross-section of gas pipeline. An improved mathematical model is also proposed by the authors, which considers the change in the gas flowrate along the gas pipeline. Complex 1 characterizing the effect of frictional forces and pressure losses and Complex 2 determining the effect of flow velocity were proposed to confirm the need to use an improved mathematical model. Based on the ratio of these complexes, a quantitative criterion was formed for the application of the improved mathematical model. An example of a comparison of complexes for a long pipeline and a short pipeline with a large gas flowrate is presented. Provided that the complexes are of the same order, the relative deviation of the pressures at the end of the gas pipeline obtained by the known and improved model can differ by 8 – 10%. Therefore, in such a case, it is necessary to apply the mathematical model improved by the authors. An example of the application of mathematical models is presented for the analysis of gas pressure and temperature distribution along a gas pipeline with significant damage. The pressure profile along this gas pipeline was obtained for its operating mode with gas flowrate limitation at the inlet and without limitation. It is shown that when the area of damage increases, the change in the pressure profile for these operating modes has features that can be used during the development of a system for determining the volume of gas lost because of sudden damage to gas pipelines.

Keywords: gas pipeline damage; mathematical model; pressure profile, measurement of gas parameters; lost gas volume.

1. Definition of the problem to be solved

Natural gas extracted from the depths of the earth can travel hundreds or even thousands of kilometers to the final consumer. Pipelines are the most economical type of gas transportation from the extraction and production areas to the use and processing areas. The main advantages of pipeline transportation are the continuity of the pumping process, high efficiency of transportation and storage, full automation of the transportation process, reliability and environmental friendliness. However, during the operation of gas pipelines, damage may occur because of the influence of technogenic and natural factors, which lead to gas losses, and disruption of the transportation process and regime, which as a result causes additional losses to gas transportation and gas distribution enterprises.

We should also note the negative impact of natural gas leaks on the environment. Methane, which is the main component of natural gas, has a strong greenhouse effect [1], [2]. Methane emissions from natural gas transportation systems are a significant source of air pollution that damages the environment, accelerates global warming, and harms human health. Do not forget about the explosive characteristics of gas. The aging of gas pipelines and the increase in

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their accident rate can lead to serious consequences. Gas leakage caused by damage because of corrosion or human negligence during the repair or laying and connecting of gas pipelines can cause their destruction and lead to people's deaths.

Today, the problem of leaks detecting and measuring the amount of gas losses from gas pipeline networks is relevant because of growing natural gas prices. To determine the volume of natural gas losses caused by damage to the gas pipeline, it is necessary to determine the gas parameters (pressure, temperature and compressibility factor) at the damage point. The complex configuration of gas pipeline networks and the lack of means for measuring gas parameters in many sections do not allow for quick detection and elimination of damage. It is impossible to determine the amount of lost gas based on the balance equation. Therefore, it is necessary to develop mathematical models for calculating the parameters of natural gas along the gas pipeline, which can be used for determining the volume of lost gas.

2. Analysis of the recent publications and research works on the problem

Lots of research is devoted to the study of gas losses, the distribution of natural gas parameters along the length of the damaged gas pipeline [3] – [15]. Special attention is paid to mathematical models that allow you to calculate gas parameters at any point of the gas pipeline, for example, at the point of damage.

Modern mathematical models and algorithms for calculating natural gas losses caused by gas pipeline damage are proposed in [8] – [12]. In [9], mathematical models of steady-state gas flow along the gas pipeline section were presented and a comparison of the known mathematical model with an improved model that considers the change in flow velocity along the gas pipeline was made. However, this research does not investigate the change in pressure distribution in a gas pipeline with damage. Mathematical models for determining the gas pressure at the pipeline damage point were developed in [4], [10], [11]. The pressure changes caused by the gas leak led to a difference in the pipeline pressure profile for the undamaged and damaged pipeline. A method for constructing profiles of gas parameters for leak detection and localization was proposed there. In [12], a model of acoustic wave propagation in a pipeline was developed considering gas viscosity for the identification of pipeline defects. The paper proposes to use pattern recognition algorithms to detect and localize damage in a gas pipeline using a physical device based on acoustic emission. However, the authors do not provide specific recommendations for applying this approach.

Many studies are devoted to the development of methods and techniques for determining the volume of natural gas losses from gas pipelines. In [6], the volumes of gas losses in gas transportation and gas distribution networks were investigated, the components of the balance equation of the gas volume were analyzed and the uncertainty analysis of each component of the balance equation was performed. The authors propose a simplified model for estimating gas volume imbalance in gas pipeline networks.

The work [13] presents the results of the development of the technique for determining the amount of natural gas in pipeline sections with complex configurations. Mathematical models are proposed for determining the amount of gas, which can also be used to determine gas parameters in each pipeline cross-section. In [14], a modified method is proposed for detecting leaks in gas pipelines with variable conditions based on the Hammerstein model. Application of this model based on monitoring of pressure and mass flowrate allows for localization of even small gas leaks in long gas pipelines with variable conditions. In the future, this model can be refined to determine the amount of gas losses caused by leakage from the gas pipeline. The research [15] presents a method of monitoring gas leaks based on a mathematical model of unsteady gas flow in a pipeline. The leak detection method is based on the comparison of the measured values with the values obtained from the pipeline simulation model. The presented algorithm requires measurement of flow parameters, pressure and temperature at the inlet and outlet of the pipeline. The amount of gas leakage is calculated from the moment when the flowrate deviation exceeds the limit value of the measurement error.

The results of the analysis of publications indicate the relevance of the task of developing mathematical models for natural gas flow in gas pipelines.

3. Formulation of the goal of the paper

Therefore, the purpose of this paper is to use the mathematical model of gas flow in gas pipelines improved by the authors for investigating the changes in natural gas parameters along a damaged gas pipeline based on the results of gas parameter measurements at gas pipeline network nodes. The work also solves the task of forming criteria for choosing a mathematical model for analyzing changes in gas parameters along the damaged gas pipeline.

4. Investigating the changes in flow parameters along the gas pipeline

Mathematical models of steady-state gas flow along the gas pipeline section are considered in [9]. The presented differential equation for determining natural gas pressure distribution in a gas pipeline in a stationary isothermal mode is obtained based on a system of equations formed from the equation of conservation of mechanical energy of an isothermal gas flow, the equation of flow continuity and the state equation of real gas. The differential equation of the temperature change along the inclined section of the gas pipeline is obtained from the heat balance equation for this section. These equations, together with the gas state equation, which determines the compressibility factor depending on the gas state parameters and its composition, form a system of equations for determining the change in gas pressure and temperature along the inclined section of the pipeline

$$\begin{cases} \dfrac{dp}{dx} = -\left[\dfrac{M \cdot g \cdot \Delta y \cdot p^2}{z \cdot R \cdot T \cdot L} + \dfrac{8 \cdot \lambda \cdot q_m^2 \cdot z \cdot R \cdot T}{M \cdot \pi^2 \cdot D^5 \cdot p}\right]; \\ z = f\left(p, T, w_{N2}, w_{CO2}, \rho_{bc}\right); \\ \dfrac{dT}{dx} = -\left[\dfrac{k_t \cdot \pi \cdot D_{outer}}{q_m \cdot c_p}\left(T - T_{am}\right) - D_i \cdot \dfrac{dp}{dx} + \dfrac{g \cdot \Delta y}{c_p \cdot L}\right]. \end{cases} \quad (1)$$

where p is the natural gas pressure in the pipeline; g is the acceleration due to gravity; M is the molar mass of natural gas; R is the gas constant; z is the compressibility factor of natural gas; T is the absolute temperature of natural gas; T_{am} is the ambient temperature; Δy is the difference between the final y_2 and initial y_1 heights of the gas pipeline placement; L is the length of the pipeline; D is the internal diameter; D_{outer} is the outer diameter of the pipeline; λ is the hydraulic resistance coefficient; q_m is the mass flowrate of gas; k_t is the heat transfer coefficient from gas to ambient; D_i is the Joule–Thomson coefficient; c_p is the gas isobaric heat capacity; ρ_{bc} is the natural gas density at base conditions, kg/m^3; w_{N2}, w_{CO2} are the molar fraction of nitrogen and carbon dioxide. The compressibility factor of natural gas can be determined by using one of the state equations in DSTU ISO 12213 [16] or DSSDD 4-2002 [17].

However, the mathematical model (1) does not consider the change in gas velocity along the gas pipeline, and this leads to an error in pressure and temperature calculation during significant pipeline damage when the pressure difference at the pipeline beginning and at the damage point can be significant. Therefore, the authors considered the change in the gas velocity in the pressure and temperature distribution equations along the pipeline.

Thus, the system of equations that allows one to determine the change in gas parameters along the gas pipeline, considering the change in the natural gas velocity, has the following form:

$$\begin{cases} \dfrac{dp}{dx} = -\left[\dfrac{M \cdot g \cdot \Delta y \cdot p^2}{z \cdot R \cdot T \cdot L} + \dfrac{8 \cdot \lambda \cdot q_m^2 \cdot z \cdot R \cdot T}{M \cdot \pi^2 \cdot D^5}\right] \Big/ \left(p - \dfrac{16 \cdot q_m^2 \cdot z \cdot R \cdot T}{p \cdot M \cdot \pi^2 \cdot D^4}\right); \\ z = f\left(p, T, w_{N2}, w_{CO2}, \rho_{bc}\right); \\ \dfrac{dT}{dx} = -\left[\dfrac{k_t \cdot \pi \cdot D_{outer}}{q_m \cdot c_p}\left(T - T_{am}\right) - \left(D_i + \dfrac{16 \cdot q_m^2 \cdot z^2 \cdot R^2 \cdot T^2}{c_p \cdot M^2 \cdot \pi^2 \cdot D^2 \cdot p^3}\right)\dfrac{dp}{dx} + \dfrac{g \cdot \Delta y}{c_p \cdot L}\right]. \end{cases} \quad (2)$$

To determine the type of model for calculating flow parameters along the gas pipeline, we propose complex (3), which characterizes the influence of friction forces and corresponding pressure losses, and complex (4), which determines the influence of flow velocity:

$$Compl_1 = \lambda \frac{L}{D}; \quad (3)$$

$$Compl_2 = 2 \ln \frac{P_1}{P_2}, \quad (4)$$

where P_1 and P_2 are the initial and final pressure values.

Comparing the numerical values of these components allows us to establish the expediency of considering the gas velocity change in the pipeline and applying the model (2). The velocity change in the gas pipeline is neglected in the case when the numerical value of component $Compl_1$ is of much greater order than the numerical value of component $Compl_2$. In the case when the numerical values of these components are of the same order, the change in the natural gas velocity must be considered.

To estimate the difference in flow parameters determined by systems (1) and (2), we calculate the relative error for pressure and temperature using formulas (5) and (6):

$$\delta_P = \frac{P_{2(1)} - P_{2(2)}}{P_{2(2)}} \cdot 100\% \, ; \tag{5}$$

$$\delta_T = \frac{T_{2(1)} - T_{2(2)}}{T_{2(2)}} \cdot 100\% \, , \tag{6}$$

where $P_{2(1)}$ is the pressure at the end of the gas pipeline section found by (1); $P_{2(2)}$ is the pressure at the end of the gas pipeline section found by (2); $T_{2(1)}$ is the temperature at the end of the gas pipeline section found by (1); $T_{2(2)}$ is the temperature at the end of the gas pipeline section found by (2).

The model based on the system of equations (1) or (2) makes it possible to analyze the distribution of pressure, temperature and compressibility factor along the horizontal or inclined section of a gas pipeline without gas removal. The authors considered an example of the application of the proposed models for the analysis of changes in flow parameters in a gas pipeline, the characteristics of which are presented in Table 1.

Table 1. Long gas pipeline characteristics and gas flow parameters

Parameter	Symbol	Value	Unit
Inner diameter of the pipeline	D	0.3	m
Outer diameter of the pipeline	D_{outer}	0.33	m
Pipeline inlet pressure	P_{in}	1.2	MPa
Natural gas temperature	T	283.15	K
Ambient temperature	T_{am}	287.15	K
Gas flowrate	Q	10000	m^3/h at base conditions
Pipeline length	L	10000	m
Distance to damage	L_d	5000	m

The simulation as part of this study was carried out using MATLAB software for numerical analysis. The pressure and temperature distribution along the horizontal section of the gas pipeline obtained by solving system (1) are the results of the simulation (see Fig.1, Fig.2).

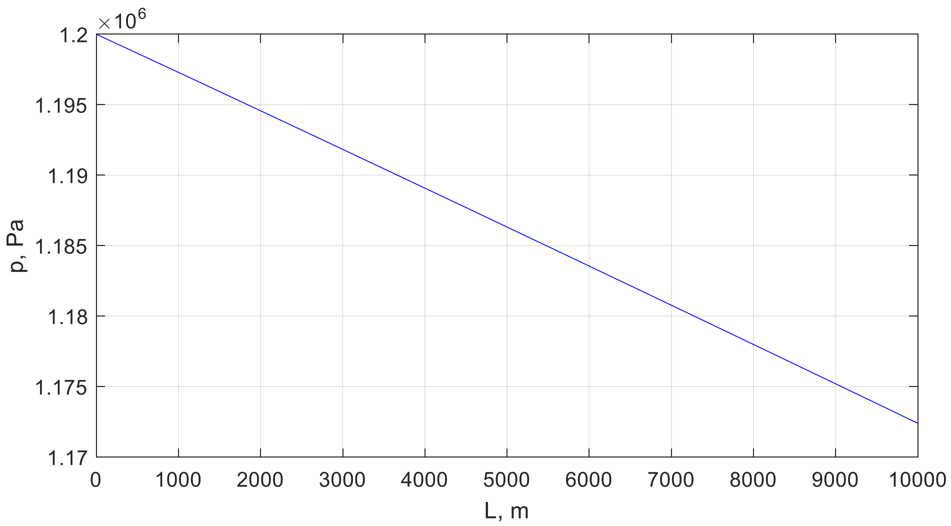

Fig.1. Pressure distribution along the undamaged gas pipeline section.

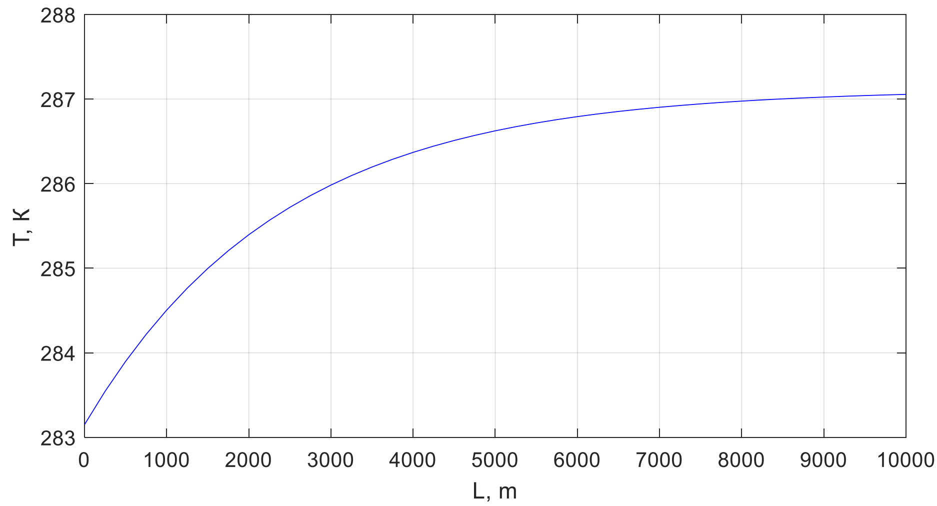

Fig. 2. Temperature distribution along the undamaged gas pipeline section.

Using this model, it is possible to illustrate the change in pressure distribution during gas pipeline damage. For this, it is necessary to know the gas parameters at the damage point. Gas losses are expressed as a percentage of the transit flowrate.

For the mode of operation of the gas pipeline section, when the maximum throughput of the control valve is reached (gas flowrate limitation at the inlet), it is impossible to compensate for pressure losses by increasing the throughput of the pressure regulator. Accordingly, the initial flowrate remains constant. One can see from Fig.3 that a break in the pressure profile occurs at the point of flowrate change (that is the leakage location). At the same time, the greater the leakage flowrate is, the greater the fracture angle of the pressure distribution will be.

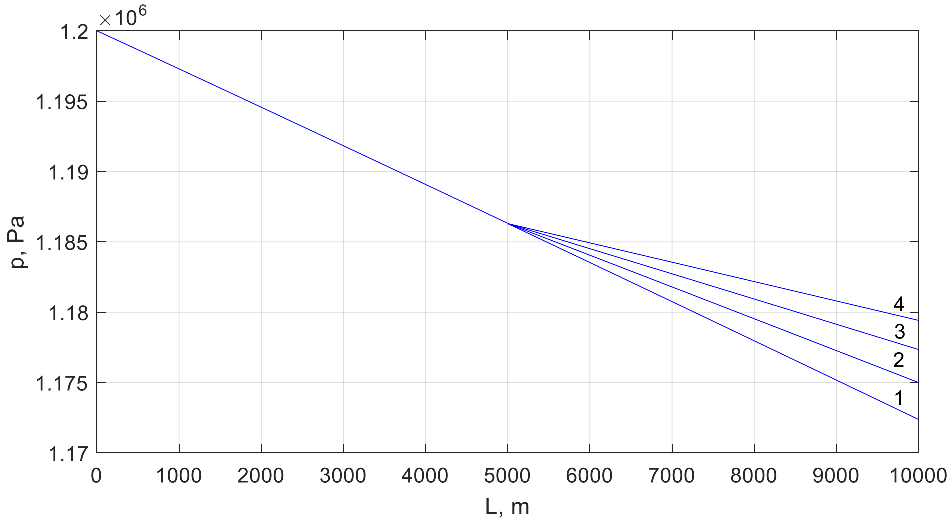

Fig.3. Pressure distribution along the gas pipeline section: without leakage (line 1, Q_{leak}=0%), with leakage of 10% (line 2), 20% (line 3), 30% (line 4) of the transit flowrate for the gas flowrate, which corresponds to the maximum throughput of the pressure regulator.

If there is no valve at the inlet to the damaged area for limitation of the gas flowrate, when damage occurs, the gas flowrate at the inlet to the area increases. The authors used a mathematical model (2) to simulate such a case. The simulation results show that there is a change in the pressure distribution both upstream and downstream of the gas leakage (see Fig.4). Therefore, regardless of the operation mode of the gas pipeline section, the gas parameters (pressure, temperature) at the pipeline damage point are significantly different from the parameters at the nodal points. Therefore, to determine the gas flow caused by damage with a known area, it is necessary to determine the gas parameters at the pipeline damage point based on the measured values of the parameters at the nodal points of the network.

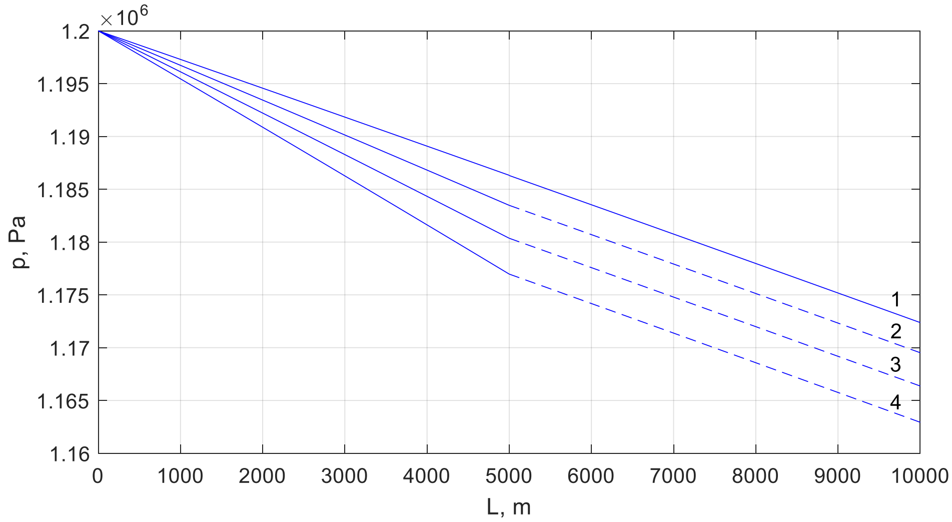

Fig.4. Pressure distribution along the gas pipeline section: without leakage (line 1), and with leakage of 10% (line 2), 20% (line 3), 30% (line 4), for gas flowrate less than the throughput of the pressure regulator.

In the case of sudden significant leaks from gas pipelines, it is necessary to use a model that considers the change in gas velocity along the gas pipeline built based on the system of equations (2).

To compare the models built on the systems of equations (1) and (2), we have determined the values of the complexes and calculated the relative error for gas pressure and temperature. The gas flow parameters and the characteristics of the long gas pipeline are shown in Table 1. The gas flow parameters and the characteristics of the short gas pipeline are given in Table 2.

Table 2. Short gas pipeline characteristics and gas flow parameters

Parameter	Symbol	Value	Unit
Inner diameter of the pipeline	D	0.3	m
Outer diameter of the pipeline	D_{outer}	0.33	m
Pipeline inlet pressure	P_{in}	1.2	MPa
Natural gas temperature	T	283.15	K
Ambient temperature	T_{am}	287.15	K
Gas flowrate	Q	115000	m^3/h at base conditions
Pipeline length	L	1500	m

The obtained simulation results for the parameters of the short gas pipeline are compared in Table 3. When applying the improved system of equations (2) for a short gas pipeline with a large flowrate we obtain the pressure and temperature at the end of the gas pipeline, which differ by 8.72% and 0.95%, respectively, from the pressure and temperature obtained by a simplified system of equations.

Table 3. Simulation results

Parameter	Long pipeline	Short pipeline
Hydraulic resistance coefficient, λ	0.0183	0.0179
Pressure at the outlet of the pipeline, P_2, MPa	1.1724	0.39818
Complex $\lambda \cdot L/D$	305.7838	89.3538
Complex $2 \cdot \ln(P_1/P_2)$	0.0465	2.2064
Relative error of pressure calculation, δ_P, %	$1.812 \cdot 10^{-4}$	8.7194
Relative error of temperature calculation, δ_T, %	$0.102 \cdot 10^{-4}$	0.9481

Damage to the gas pipeline can occur at different distances from the gas supply source, particularly at short distances. Then the hydraulic regime of the gas pipeline section between the supply source and the damage is close to the example considered for a short gas pipeline. Therefore, it is recommended to use the system of equations (2) to calculate flow parameters during damage to gas pipelines.

5. Conclusion

By combining the developed differential equations for changes in gas pressure and temperature along the gas pipeline, as well as the equation for calculating the compressibility factor of natural gas, a mathematical model of the steady-state flow of natural gas in an inclined gas pipeline was obtained, which makes it possible to calculate the gas parameters (pressure, temperature, compressibility factor) in every gas pipeline cross-section based on the flow parameters measured at nodal points of the gas pipeline network.

The authors improved this mathematical model to consider the change in the gas flowrate along the gas pipeline. To confirm the necessity of using an improved mathematical model, the authors proposed a complex characterizing the influence of friction forces and pressure losses, and a complex determining the influence of the flowrate. Based on the ratio of these complexes, a quantitative criterion was formed for the application of the improved mathematical model.

Using the improved mathematical model of gas flow makes it possible to study the distribution of gas parameters along a gas pipeline with significant gas flowrate caused by technological gas removals or damage to the gas pipeline. Therefore, it is the basis for the development of an instrument system for determining the volume of gas lost because of sudden damage to gas pipelines.

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Дослідження зміни параметрів природного газу вздовж газопроводу з пошкодженнями

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Анотація

У роботі представлено математичну модель стаціонарного руху природного газу у похилому газопроводі, яка дає можливість обчислити значення параметрів газу (тиску, температури, фактора стисливості) у довільному перерізі газопроводу. Представлено також удосконалену авторами математичну модель, яка враховує зміну швидкості потоку газу вздовж газопроводу. Для підтвердження необхідності застосування удосконаленої математичної моделі виділено Комплекс 1, який характеризує вплив сил тертя та втрат тиску, та Комплекс 2, який визначає вплив швидкості потоку. На основі співвідношення цих комплексів сформовано кількісний критерій застосування удосконаленої математичної моделі. Представлено приклад порівняння комплексів для довгого газопроводу та короткого газопроводу з великою витратою газу. Показано, що за умови коли значення комплексів є одного порядку, відносне відхилення значень тиску в кінці газопроводу отриманих за відомою та удосконаленою моделлю можуть відрізнятися на 8 – 10%. Отже у такому випадку потрібно застосовувати удосконалену авторами математичну модель. Представлено приклад застосування математичних моделей для аналізу розподілу тиску та температури газу вздовж газопроводу зі значними пошкодженнями. Отримано профіль зміни тиску вздовж цього газопроводу для режиму його експлуатації з обмеженням витрати газу на вході та без обмеження. Показано, що при збільшенні площі пошкодження зміна профілю тиску для цих режимів експлуатації має характерні особливості, які можуть бути використані під час розроблення системи визначення об’єму газу, втраченого внаслідок раптових пошкоджень газопроводів.

Ключові слова: пошкодження газопроводу; математична модель; профіль тиску; вимірювання параметрів газу; об’єм втраченого газу.