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FORECASTING RATIONAL WORKING MODES OF LONG-OPERATED GAS-TRANSPORT SYSTEMS UNDER CONDITIONS OF THEIR INCOMPLETE LOADING

Volodymyr Grudz
Doctor of Technical Sciences, Professor*

Yaroslav Grudz
Doctor of Technical Sciences, Professor*

Myroslav Iakymiv
Director**

Mykola Iakymiv
Corresponding author
PhD*
Society of Petroleum Engineers member, Deputy Director for Foreign Economic and Commercial Affairs**
E-mail: m.iakymiv@googlemail.com

Pavlo Iagoda
Deputy Director for Dispatching, Head of Department
Gas Transmission System Operator of Ukraine LLC
Liubomyra Huzara ave., 44, Kyiv, Ukraine, 03065

*Department of Oil and Gas Pipelines and Storage Facilities
Ivano-Frankivsk National Technical University of Oil and Gas
Karpatska str., 15, Ivano-Frankivsk, Ukraine, 76019

**GEOGAZCENTR LLC
Turivska str., 18/20, Kyiv, Ukraine, 04080

Prolonged operation of the gas-transport system in conditions of partial loading involves frequent changes in the volume of gas transportation, which necessitates prompt forecasting of system operation.

When forecasting the modes of operation of the gas transport system, the main criterion of optimality implies the maximum volume of gas pumping. After all, in this case, the largest profit of the gas-transport company is achieved under the condition of full provision of consumers with energy.

In conditions of incomplete loading of the gas-transport system caused by a shortage of gas supply, optimality criteria change significantly. First, the equipment is operated in ranges far from nominal ones which leads to growth of energy consumption. Secondly, changes in performance cause high-amplitude pressure fluctuations at the outlet of compressor stations.

Based on mathematical modeling of nonstationary processes, amplitude and frequency of pressure fluctuations at the outlet of compressor stations which can cause the pipeline overload have been established. To prevent this, it was proposed to reduce initial pressure relative to the maximum one. Calculated dependence was obtained which connects the amplitude of pressure fluctuations with the characteristics of the gas pipeline and the nonstationary process.

Reduction in energy consumption for transportation is due to the shutdown of individual compressor stations (CS). Mathematical modeling has made it possible to establish regularities of reduction of productivity of the gas-transport system and duration of the nonstationary process depending on the location of the compressor station on the route. With an increase in the number of shutdown compression stations, the degree of productivity decrease and duration of nonstationarity reduces.

The established patterns and proposed solutions will improve the reliability of a gas-transport system by preventing pipeline overload and reduce the cost of gas transportation by selecting running numbers of shutdown stations with a known decrease in productivity

Keywords: gas-transport system, compressor station, linear section, incomplete loading, nonstationary process

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1. Introduction

The gas-transport system as a part of the trans-European gas complex is currently in the process of reforming and reorganizing its functional use. The root cause of this situation consists in a significant expansion of the Eurasian gas supply system having a throughput of its gas pipelines significantly exceeding the volume of production and consumption of natural gas on the continent which makes it possible to vary directions of gas flows. On the other hand, a gradual decline in gas production leads to an increase in demand and growth of prices for energy carriers and raw materials which requires economical gas consumption. Because of this, gas-transport systems cannot function as before at full load for a long period of time (e.g., a year). The development of vital interests of mankind requires flexibility in the functioning of the gas supply system which primarily determines its operation modes with loading varying in time.

Let us consider an example. Ukraine has explored reserves of natural gas amounting to about a trillion cubic meters including the use of liquefied and compressed gas transported by sea. However, gas production from these reserves in combination with alternative sources of gas supply requires a significant adjustment of gas flows and constant changes in the system operation modes. In such conditions, the main principles of operation of the gas-transport complex should include reliability and energy efficiency. Realization of these principles requires the solution of a number of scientific and technical problems of optimization and forecasting nature.

2. Literature review and problem statement

In conditions of incomplete loading of gas-transport system, minimum energy consumption for gas transportation and maximum pipeline reliability can be only criteria of operating mode optimality. This issue is reflected in detail in [1]. According to the first criteria, the principle of optimization of modes should be changed.

As is known from a scientific study [2], the total capacity of compressor stations (CS) decreases when operating pressures in the pipeline increase and reaches a minimum value at a maximum allowable pressure at the outlet of compressor stations. Thus, as noted in [3], in terms of minimizing energy consumption for gas transportation in conditions of incomplete loading of the gas-transport system, it is necessary to choose modes with maximum allowable pressures at the outlet of compressor stations.

Conclusion concerning the expediency of gas transportation at high pressures in terms of minimizing energy consumption for transportation has a physical explanation. Gas density increases at high pressures (under other conditions being identical) [4] which at a steady flow of gas leads to a decrease in the linear speed. The magnitude of this decrease has an effect on hydraulic pressure loss caused by friction [5]. Therefore, the optimal mode of operation should be characterized by high pressure values which cannot always be realized in terms of operational safety [6].

However, under the conditions of incomplete loading of the gas-transport system, pressure changes are possible in a wide range [7] at constant productivity. Information on efficiency and reliability was not found in the literature. Therefore, as was established in [8], it is advisable to conduct studies of nonstationary processes taking place in gas pipelines in order to assess energy efficiency and system operation reliability.

The range of possible pressure fluctuation is limited by a line of depression at maximum initial pressure from above and by a line of depression at minimum final pressure from below [9] which determine the field of permissible modes [10]. Violation of this range by exceeding the allowable pressure can lead to pipeline destruction or to a failure of the normal operation of centrifugal superchargers at the CS by lowering the pressure below the minimum allowable value. The process of formation of a pressure drop at a current moment of productivity change is nonstationary and characterized by pressure fluctuations with a certain frequency and amplitude. Superposition of pressures can lead to excessive initial pressure at the top limit line of depression or to a pressure drop below the allowable value at the bottom limit line of depression which is not taken into account in [11].

To assess the nature of pressure fluctuations, a mathematical model of a nonstationary process occurring in a gas-transport system [12] caused by a change in productivity under noncomplete loading was constructed. Its implementation for real conditions of gas pipeline operation has made it possible to establish the amplitude and frequency characteristics of the oscillating process [13]. It was found in [3] that amplitude can exceed 1 MPa in the low-frequency region of pressure fluctuations which will lead to an absolute value of pressure outside the allowable range. In addition, it should be borne in mind that perturbation velocities in a pipeline will differ considerably at high and low pressures which will affect frequency characteristics of the nonstationary process [4]. In this regard, [5] does not provide recommendations concerning pipeline protection against excessive pressures.

Despite the energy efficiency characteristics of gas transportation at high pressures, it is desirable to leave a certain margin of possible amplitude fluctuation of pressure to prevent it from going beyond the limit lines of depression.

Thus, the problem of choosing economic modes of operation and ensuring the reliability of gas pipelines in conditions of pressure fluctuations caused by productivity changes and CS shutdown in conditions of incomplete loading of gas-transport systems must be solved.

3. The aim and objectives of the study

The study objective implied establishing patterns of nonstationary processes in gas-transport systems for safe and energy-efficient control of operating modes in conditions of partial system loading.

This objective was achieved through the solution of the following study tasks:

– establish patterns and characteristics of pipeline pressure fluctuations when gas flow rate changes;

– conduct an analytical study of the influence of disconnection of a compressor station from the mode of operation of a gas transport system on the nature of the nonstationary process behavior;

– establish magnitude and margin of pressure at the CS outlet to prevent pipeline overload.

4. The study materials and methods

To solve the above tasks, an analytical approach was applied using a mathematical model of nonstationary isothermal one-dimensional gas motion in a pipeline. To construct a mathematical model for assessing the nature of pressure fluctuations over time and along the pipeline length in conditions of fluctuation of the gas flow rate and CS shutdown, assumptions of unidimensionality and isothermality of a gas flow, as well as neglect of Coriolis and gravitational energy losses, were taken [9].

To test this model, a computational experiment was conducted on the basis of the Soyuz gas main. To construct dependence of the amplitude of pressure fluctuations on the pipeline characteristics and the mode parameters, methods of the similarity theory and rational experiment planning were applied.

The influence of the location of a shutdown CS in the pipeline route on the degree of reduction of the gas-transport system throughput and duration of the nonstationary process was established based on obtained analytical solutions. This has made it possible to rationally forecast the system operation modes at a specified performance.

5. The results obtained in studying the pressure fluctuations

5. 1. Study of a nonstationary process in a gas pipeline caused by a change in gas take-off

The magnitude of the amplitude of pressure fluctuations depends on the magnitude of abrupt change of gas flow rate as a perturbation factor, coordinates of perturbations, absolute values of pressure and temperature, and physical properties of the gas.

The mathematical model of nonstationary isothermal one-dimensional gas motion in the pipeline can be represented as a system of the following equations [2]:

$$\frac{\partial p}{\partial x}+\rho\alpha\frac{\partial}{\partial x}\left(\frac{\omega^2}{2\rho^2}\right)+\beta\rho g\frac{\partial h}{\partial x}+\frac{\lambda\omega^2}{2\rho D}+\gamma\frac{\partial \omega}{\partial t}=0,$$

$$\frac{\partial \omega}{\partial x}+\frac{1}{c^2}\frac{\partial p}{\partial t}=0, \qquad (1)$$

where $p=p(x, t)$ is pressure as a function of the linear coordinate x and time t; ω is linear gas speed; λ is coefficient of hydraulic resistance; ρ is gas density; D is the diameter; h is geodetic profile mark; $c=\sqrt{kzRT}$ is the speed of sound in gas; α is Coriolis coefficient (α=2 for laminar flow and α=1.1 for turbulent flow).

The first equation takes into account friction forces, the difference in the pipeline heights, and inertial resistance. The second equation characterizes the quantitative balance of gas. The dependence of temperature change on the pipeline length was taken into account based on constructing an iterative algorithm. Coefficients β and γ in system (1) were introduced to study the influence of respective compound forces.

When ignoring the influence of gravitational and Coriolis forces, system (1) is reduced to the following equation:

$$\frac{\partial^2 P}{\partial x^2}=\frac{2a}{c^2}\frac{\partial P}{\partial t}+\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2}, \qquad (2)$$

where $2a$ is the linearization coefficient

$$2a=\frac{\lambda\omega}{2D}.$$

Equation (2) reflects the oscillating process of pressure function in space and time. It is known in mathematical physics as a telegraph equation.

Note that pressure fluctuations in the gas flow can have different frequencies and amplitudes depending on what was their cause. In accordance with the above, pressure fluctuations are conventionally divided into high-frequency, medium-frequency, and low-frequency fluctuations. High-frequency fluctuations are characterized by a frequency within 0.4–4.0 Hz and are usually caused by an abrupt change in a parameter (pressure, flow rate) at a certain section of the gas pipeline. The amplitude of such oscillations can reach 1 MPa. Oscillations propagate along the pipeline at the speed of sound while amplitude and frequency decrease. The medium-frequency range is within 0.5–10 Hz. Such fluctuations cause smooth changes in flow parameters over time. They propagate along the pipeline with a substantially smaller decay decrement. Low-frequency oscillations are caused by uneven daily gas consumption and are in the frequency range of 10^{-5}–0.5 Hz. The amplitude of pressure fluctuation depends on the perturbation factor's nature and can be limitless (e.g., for conditions of filling a pipeline section with gas). Under conditions of high-frequency oscillations, inertial forces, and forces of hydraulic resistance in the gas flow play a crucial role in the process formation. Hydraulic resistance of the pipeline is the main source of medium- and low-frequency oscillations. In terms of ensuring reliable operation of the gas transport system, high-frequency fluctuations of pressure play a crucial role because this process is the most unpredictable.

Since frequency and amplitude of pressure fluctuations caused by perturbations of the gas flow parameters are characteristics of a nonstationary process, there must be a relationship between amplitude-frequency characteristics and the criterion of non-stationarity [4].

The optimization problem consists in determining rational values of the stationary process pressures in the gas pipeline at which minimum energy consumption for transportation is achieved on the one hand and reliability of operation is ensured on the other hand. As noted, maximum possible pressures in gas pipelines will make it possible to minimize hydraulic losses during gas transportation, i.e. achieve minimum energy consumption. However, pressure fluctuations in nonstationary processes caused by abrupt changes in parameters (most often, gas flow rate under conditions of partial loading) can go beyond the limits of allowable loads in terms of ensuring strength. Therefore, it is necessary to choose such maximum possible pressures of the stationary process in gas pipelines at which the result of superposition with an amplitude value of pressure in the nonstationary process would not bring the value of pipe wall loading beyond the allowable limits.

This formulation of the problem requires the solution of equation (2) under the following initial and boundary conditions chosen for the underwritten reasons. Prior to the start of the nonstationary process caused by perturbation of the gas flow, the gas pipeline was operated in a stationary technological mode with the distribution of pressures along its length according to the parabolic law.

$$P(x,0)=\sqrt{P_H^2-\left(P_H^2-P_K^2\right)x/L}, \qquad (3)$$

where $P(x,0)$ is the pressure at a distance x from the beginning of the pipeline having length L; P_H, P_K are pressures at the beginning and end of the pipeline, respectively.

At given pressures P_H, P_K respectively at the pipeline beginning and end, a certain mass productivity Q_0 of the pipeline is provided which in conditions of incomplete loading can be changed at any time in the direction of increase or decrease by some ΔQ value. Suppose that gas take-off to the pipeline has not changed starting from a certain point in time $t>0$ and gas take-off at the end of the route has changed by a known amount ΔQ. Then boundary conditions for the solution of equation (2) will look like:

$$Q(0,t)=Q_0, \quad Q(L,t)=Q_1, \qquad (4)$$

where

$$Q_1=Q_0+\Delta Q.$$

Using the first equation of system (1) and neglecting all types of energy consumption except hydraulic resistance, the following is obtained:

$$-\frac{\partial P}{\partial x_{x=0}}=\frac{2a}{F^2}Q_0; \qquad (5)$$

$$-\frac{\partial P}{\partial x_{x=L}}=\frac{2a}{F^2}Q_1;$$

$$F = \frac{\pi D^2}{4}$$

is the cross-sectional area of the pipeline.

Solution (2) under these initial and boundary conditions is sought by the Fourier method and takes the following form:

$$P(x,t) = \frac{\lambda \rho w}{2dF^2} x \left(Q_0 - \frac{Q_0 - Q_L}{2L} x \right) + \frac{2}{L} \sum_{n=1}^{\infty} \left\{ \begin{array}{l} \int_0^L \sqrt{P_H^2 - \left(P_H^2 - P_K^2\right) x / L} \cos \frac{\pi n x}{L} dx - \\ -\frac{\lambda w}{\pi n F} \left[Q_0 \left(1 - (-1)^n \right) \right] - \\ -\frac{1}{2\pi n} \left[(Q_0 - Q_L)(-1)^n \right] \end{array} \right\} \times$$

$$\times \exp\left(-\frac{\lambda w}{4d} t \right) \sin \left[\begin{array}{l} \frac{\lambda w}{4d} t \times \\ \times \sqrt{\left(\frac{4\pi m c d}{\lambda w} \right)^2 - 1} \end{array} \right] \cos \frac{\pi n x}{L}. \quad (6)$$

The obtained mathematical model makes it possible to estimate the magnitude of amplitude of pressure fluctuations along the pipeline length and in time in the event of disturbances in a form of abrupt changes in productivity at the pipeline beginning or end. It is obvious that from the point of view of safe operation of the gas pipeline, fluctuations of pressure $P(0, t)$ in the initial cross-section are of the greatest interest. The largest values of absolute pressures occur there which in superposition with amplitude oscillations can lead to exceeding the allowable load [10].

To establish the nature of the above dependences, the model was implemented at various values of the listed magnitudes taken as the model parameters. Results of the mathematical model show that when gas temperature and its main physical properties change in the ranges corresponding to the modes of operation of gas pipelines. Their influence on the magnitude of amplitude pressure fluctuations is insignificant. Therefore, operating pressure, flow rate, and linear coordinate of gas take-off should be considered the main parameters determining the magnitude of amplitude and frequency of pressure fluctuations in a nonstationary process caused by abrupt changes in the gas flow rate.

Fig. 1–3 show examples of implementation of a mathematical model for different conditions in a form of graphs of dependence of pressure fluctuations over time according to which the maximum amplitude of pressure fluctuations, process duration, and average oscillation frequency were determined. The moment of completion of the oscillating process was determined from the graphs where the amplitude decreases below one percent of the maximum. The average oscillation frequency was determined by the number of complete oscillations throughout the process.

Note that the physical properties of the gas are determined by the gas constant R and thermal conditions are determined by absolute temperature T. Then, based on the model results, it can be stated that the product RT is a characteristic parameter of the nonstationary process dynamics. In other words, when the gas constant and gas temperature change so that their product remains unchanged, the nature of the pressure fluctuations in the nonstationary process will be identical. On the other hand, the product RT characterizes the speed of propagation of small perturbations in the gas, i.e. the speed of sound $c = \sqrt{kRT}$. Therefore, to characterize the nonstationary process, it is advisable to take the speed of sound propagation in the gas stream as an independent parameter.

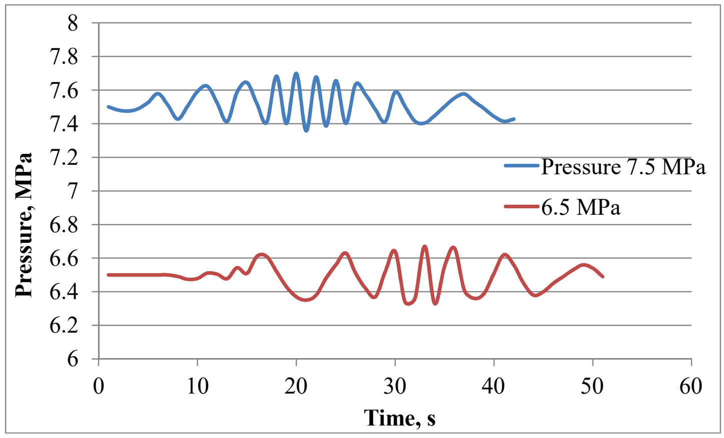


Fig. 1. Examples of the behavior of the nonstationary process at different values of initial pressure

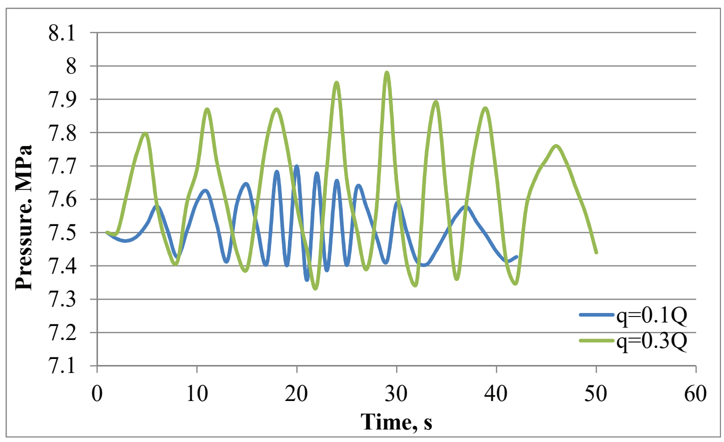


Fig. 2. Examples of the behavior of the nonstationary process at different values of gas take-off

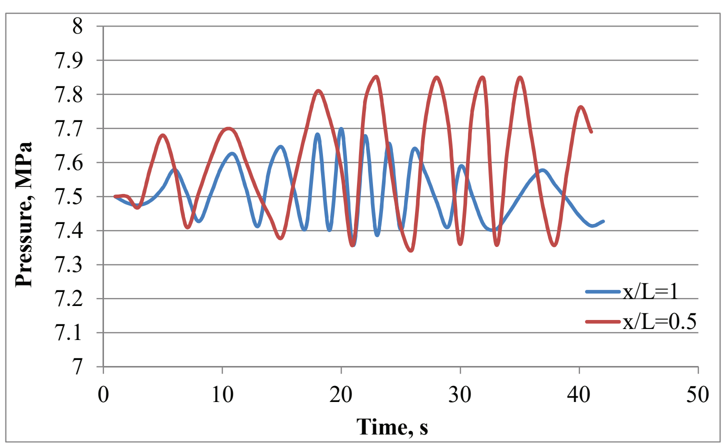


Fig. 3. Examples of the behavior of the nonstationary process at different values of the linear coordinate of gas take-off

5. 2. Studying the influence of shutdown of compressor stations on nonstationary process nature

A shutdown of individual compressor stations is one of control options. As shown in [3], the required performance of the gas-transport system can be achieved depending on the number and the serial numbers of operating stations. At the same time, given the low efficiency of the gas pumping units with gas turbine drive, a shutdown of an individual CS may be the most effective method of regulating productivity from the energy point of view. Obviously, this method can be used for seasonal regulation of productivity. It should be borne in mind that stopping and restarting the CS will require additional energy consumption.

From a technological point of view, stopping and restarting the compressor station will lead to a nonstationary process. Its duration should be predicted in order to provide consumers with gas.

When summarizing the above, it should be concluded that it is necessary to predict nonstationary processes in complex gas-transport systems of large length including a large number of compressor stations.

Prediction and analysis of such production situations in the gas-transport system, as well as assessment of energy losses, are possible only based on a mathematical model. This model is based on equations of nonstationary gas motion in pipes taking into account pressure buildup at compressor stations and the flow continuity [11].

$$-\frac{\partial P}{\partial x}+\sum_{i=1}^{m}\Delta P_{KCi}\delta(x-x_i)=\left(\frac{\partial(\rho w)}{\partial \iota}+\frac{\lambda\rho w^2}{2d}\right),$$
$$\frac{\partial P}{\partial t}=-c^2\frac{\partial(\rho w)}{\partial x}. \qquad (7)$$

The first equation in system (7) includes pressure buildup at the compressor station with coordinate x_1 and the Dirac source function modeling pressure buildup at the compressor station where ΔP_{KCi} is pressure buildup at the compressor station with coordinate x_i; $\delta(x-x_1)$ is the Dirac source function modeling pressure buildup at the compressor station.

Note that in order to model the wave attenuation processes in a gas pipeline, the equation of motion includes inertial hydraulic losses and friction losses.

The above system of differential equations (7) reduces to the following equation:

$$\frac{\partial^2 P}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2}+\frac{2a}{c^2}\frac{\partial P}{\partial t}+\sum_{i=1}^{m}\Delta P_{KCi}\delta^*(x-x_i), \qquad (8)$$

where $\delta^*(x-x_1)$ is the linear derivative of the Dirac function in linear coordinate.

Let the gas-transport system of length L contain m intermediate compressor stations which start working simultaneously at time t=0 and the station number k be switched off at time t_1. For this case, equation (8) will take the form

$$\frac{\partial^2 P}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2}+\frac{2a}{c^2}\frac{\partial P}{\partial t}+\sum_{i=1}^{m}\Delta P_{KCi}\delta^*(x-x_i)+$$
$$+\Delta P_{KCk}\delta^*(x-x_k)\left[\sigma(t)-\sigma(t-t_1)\right], \qquad (9)$$

where $\sigma(t)$ is the Heaviside unit function.

Assume that a gas pipeline was stopped at an initial moment of time and constant pressure P_0 was maintained in it at all its length. Then initial conditions will be as follow:

$$t=0,\ \ P(x,0)=P_0,\ \ \partial P/\partial x=0. \qquad (10)$$

Starting from a certain point in time $t>0$, a constant initial pressure $P(0, t)=P_H$ is maintained at the beginning of the pipeline, and a constant final pressure $P(L, t)=P_K$ is maintained at its end.

Integral transformations were used to obtain a solution of the mathematical model, in particular, the Fourier sine-transform and Laplace transform [2, 11].

Application of inverse Laplace and Fourier transforms after simple transformations enables obtaining of the following dependence of pressure change along the pipeline length and in time of the nonstationary process:

$$P(x,t)=P_0+(P_H-P_K)\frac{x}{L}+$$
$$+\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{KCi}\left\{\begin{matrix}\left(1-\frac{x}{L}\right) \text{ at } x>x_i\\ \left(-\frac{x}{L}\right) \text{ at } x<x_i\end{matrix}\right\}+$$
$$+\Delta P_{KCk}\left[\sigma(t)-\sigma(t-t_1)\right]\left\{\begin{matrix}\left(1-\frac{x}{L}\right) \text{ at } x>x_i\\ \left(-\frac{x}{L}\right) \text{ at } x<x_i\end{matrix}\right\}+$$
$$+\sum_{n=1}^{\infty}C_n e^{-at}f(n,t)\sin\left(\frac{\pi n x}{L}\right)+$$
$$+\frac{2}{\pi}\Delta P_{KCk}\sum_{n=1}^{\infty}\begin{matrix}\frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right)\times\\ \times e^{-a(t-t_1)}f(n,t-t_1)\sigma(t-t_1)\end{matrix}. \qquad (11)$$

$$f(n,t)=\cos\left(\sqrt{\left(\frac{\pi n c}{L}\right)^2-a^2}\,t\right)+$$
$$+\frac{a}{\sqrt{\left(\frac{\pi n c}{L}\right)^2-a^2}}\sin\left(\sqrt{\left(\frac{\pi n c}{L}\right)^2-a^2}\,t\right).$$

The first four terms of the solution (11) characterize the stationary mode of operation of the gas transport system. The fifth term describes the nonstationary process caused by simultaneous switching-on of all compressor stations at time t=0. The last term is for modeling the nonstationary process caused by a shutdown of the k-th compressor station starting from time t_1. The process occurring in the gas pipeline after a significant period from the moment of switching on all CSs is considered. Then initial non-stationarity will not affect the process due to the higher order of smallness of the e^{-at} factor and the solution of the problem of a shutdown of the k-th compressor station can be represented as

$$P(x,t)=P_0+(P_H-P_K)\frac{x}{L}+$$
$$+\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{KCi}\left\{\begin{matrix}\left(1-\frac{x}{L}\right) \text{ at } x>x_i\\ \left(-\frac{x}{L}\right) \text{ at } x<x_i\end{matrix}\right\}+$$
$$+\frac{2}{\pi}\Delta P_{KCk}\sum_{n=1}^{\infty}\begin{matrix}\frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right)\times\\ \times e^{-a(t-t_1)}f(n,t-t_1)\sigma(t-t_1)\end{matrix}. \qquad (12)$$

Solution (12) describes a nonstationary process caused by the shutdown of the k-th compressor station and does not take into account the impact of the initial nonstationary process of switching on all CSs in operation. Therefore, time count can be started from the moment of switching off the k-th compressor station. The following is obtained in this case:

$$P(x,t)=P_0+(P_H-P_K)\frac{x}{L}+\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{KCi}\begin{cases}\left(1-\frac{x}{L}\right) & \text{at } x>x_i\\ \left(-\frac{x}{L}\right) & \text{at } x<x_i\end{cases}+\frac{2}{\pi}\Delta P_{KCk}\sum_{n=1}^{\infty}\frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right)e^{-at}\times\left(\cos\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)+\frac{a}{\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}}\times\sin\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)\right). \quad (13)$$

Equation (13) makes it possible to predict the nature of the nonstationary process in long gas-transport systems with a large number of compressor stations caused by shutdown and re-start of one of the stations.

To estimate the duration of the nonstationary process, it is necessary to construct a dependence of variation of the mass flow rate of gas in time as the most inertial characteristic in the initial or final section of the pipeline [10].

For this purpose, use the equation of gas motion from system (7). It is obvious that the Dirac delta function is equal to zero, $\delta(x-x_1)=0$ for the initial ($x=0$) or final ($x=L$) section, therefore

$$-\frac{\partial P}{\partial x}=\frac{\partial(\rho w)}{\partial \iota}+\frac{\lambda\rho w^2}{2d}. \quad (14)$$

To simplify the computation process, neglect inertial losses in the initial and final sections, i.e. assume that $\partial(\rho w)/\partial\iota=0$ [14]. Certainly, this is connected with a certain error in the calculation of the mass flow rate of gas, however, dynamics of its change over time is important in the forecast calculations but not the absolute value of gas flow rate. In addition, the following is obtained using linearization of the equation of motion:

$$m(0,t)=-\frac{\pi d^3}{\lambda w}\frac{\partial P}{\partial x}_{|x=0},$$

$$m(L,t)=-\frac{\pi d^3}{\lambda w}\frac{\partial P}{\partial x}_{|x=L}. \quad (15)$$

The following is obtained using equation (13) after differentiation:

$$m(0,t)=-\frac{\pi d^3}{\lambda w}\left(\frac{P_H-P_K}{L}-\frac{\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{KCi}}{L}+\frac{2L}{\pi^2}\Delta P_{KCk}\times\sum_{n=1}^{\infty}\frac{1}{n^2}\cos\left(\frac{\pi n x_k}{L}\right)e^{-at}\times\left(\cos\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)+\frac{a}{\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}}\times\sin\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)\right)\right),$$

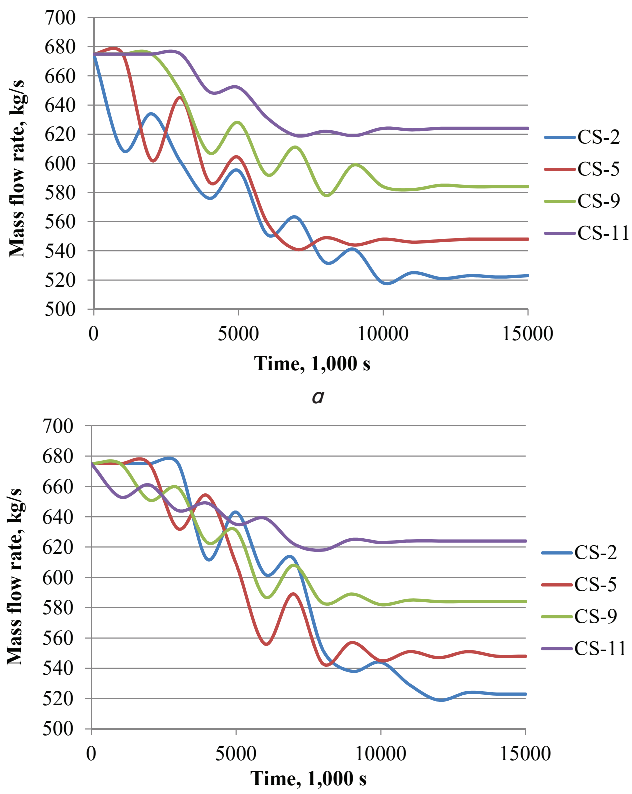
$$m(L,t)=-\frac{\pi d^3}{\lambda w}\left(\frac{P_H-P_K}{L}-\frac{\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{KCi}}{L}+\frac{2L}{\pi^2}\Delta P_{KCk}\times\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos\left(\frac{\pi n x_k}{L}\right)e^{-at}\times\left(\cos\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)+\frac{a}{\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}}\times\sin\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2-a^2}\,t\right)\right)\right). \quad (16)$$

The obtained dependences make it possible to predict the nature of fluctuation in time of the mass flow rate at the beginning and end of a long gas-transport system. It includes m intermediate compressor stations caused by shutdown or re-start of the k-th compressor station (k=1, 2,... m).

To study the influence of the number of shutdown compressor stations on the duration of the nonstationary process in the system, a computational experiment was conducted on the basis of the Soyuz gas main. Its total length is 1,567.3 km (on the territory of Ukraine). It was constructed of 1,420 mm diameter 20 mm wall thickness pipes and equipped with 13 compressor stations with GTK-10I gas pumping units installed along the pipeline route. Forecast calculations of the nonstationary processes caused by CS shutdown were performed for conditions of design operation modes. According to the calculations, the throughput of this gas pipeline measures 26 billion m^3 per year at initial pressure (at the CS outlet) of 7.5 MPa and final pressure (at the CS inlet) of 5 MPa. The pressure difference at the station (2.5 MPa) was taken the same for all CSs. The initial station (Novopskov CS-11) was considered as the main station and the other 12 as intermediate stations. The problem statement consisted in determining the nature of the pipeline performance change in time at its beginning and end at a stepping shutdown of each of intermediate CS.

The calculations performed according to the above procedure have enabled obtaining the results graphically presented in Fig. 4.

Fig. 5 shows graphs of the duration of the nonstationary process at the beginning and end of the gas-transport system with a gradual shutdown of each of the compressor stations.



a

b

Fig. 4. The behavior of the nonstationary process when shutting down compressor stations (fluctuation of mass flow rate in time): *a* – at the pipeline beginning; *b* – at the pipeline end

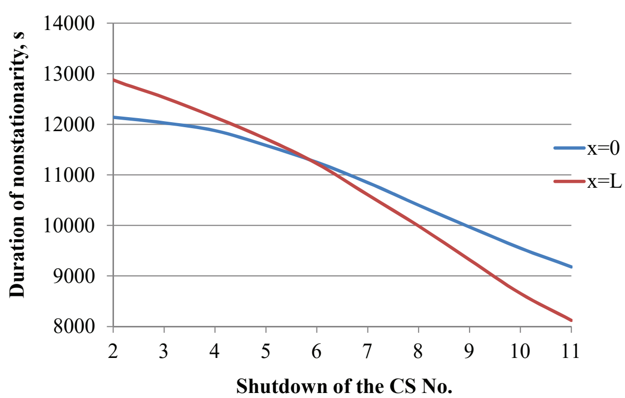


Fig. 5. Duration of the nonstationary process caused by a shutdown of compressor stations for initial (x=0) and final (x=L) sections of the pipeline

5. 3. Determining the value of pressure margin at the outlet of the compressor station to prevent the pipeline overloading

Analysis of the results obtained in modeling the nonstationary process in a gas pipeline caused by an abrupt change in gas flow rate in conditions of incomplete loading of the pipeline allows us to state the following. The amplitude of pressure fluctuation at maximum allowable stationary pressure at the beginning of the linear section of the gas pipeline can result in a short-term overload of the pipe walls, i.e. violation of safe operation of the gas-transport system will occur. Therefore, in online control of operating conditions, it is necessary to make a decision on ensuring allowable pressure at the beginning of the linear section (at the outlet of the compressor station) in cases of abrupt changes in gas flow rate. It is obvious that the implementation of the mathematical model in each of the cases of a flow rate change cannot be used in online control in order to establish the amplitude of pressure fluctuations. Therefore, for this purpose, it was proposed to construct empirical dependence of the maximum amplitude of pressure fluctuations at the beginning of the gas pipeline section (hereinafter, it will be called pressure amplitude for short) on the gas pipeline characteristics and the mode parameters.

This dependence can be obtained on the basis of the results of mathematical modeling of the nonstationary process caused by an abrupt change in gas flow rate.

Construction of empirical dependence of the pressure amplitude on the pipeline characteristics and the process parameters was performed using the method of rational experiment planning [15].

The maximum amplitude of pressure fluctuations ΔP (MPa) was considered as a response function. The following independent parameters were chosen: the value of operating pressure in the pipeline $P_{\max}$ (MPa); linear relative coordinate of take-off x/L; the speed of sound in gas c; the relative value of the take-off rate q/Q. Volume V (m^3) of a cavity of the linear section of the gas pipeline was used as its characteristic. Each of the independent parameters could take 5 concrete values in this series of experiments. Thus, functional dependences of the response function on independent parameters were built at five levels in order to obtain the following formula:

$$\Delta P = F\left(P_{\max}, V, c, x/L, q/Q\right).$$

The study results were processed according to the method using the study [15] based on the constructed dependences presented in Fig. 6, 7.

As a result, an empirical dependence of the following form was obtained using the regression methods [14]:

$$\Delta P = 0.987 V^{0.11} P_{\max}^{0.55} \times$$
$$\times \left[1-(x/L)\right]^{0.33} c^{0.04} (q/Q)^{1.28},$$

where ΔP is amplitude value of pressure buildup, MPa;

V is the geometric volume of the section cavity, mln m^3;

$P_{\max}$ is the maximum pressure in the pipeline, MPa;

c is the speed of sound in gas, m/s;

x/L is the relative distance to the gas take-off;

q/Q is the relative value of abrupt take-off.

The obtained dependence correlates well with the analytical expressions obtained on the basis of the implementation of the mathematical model. This confirms the study's validity.

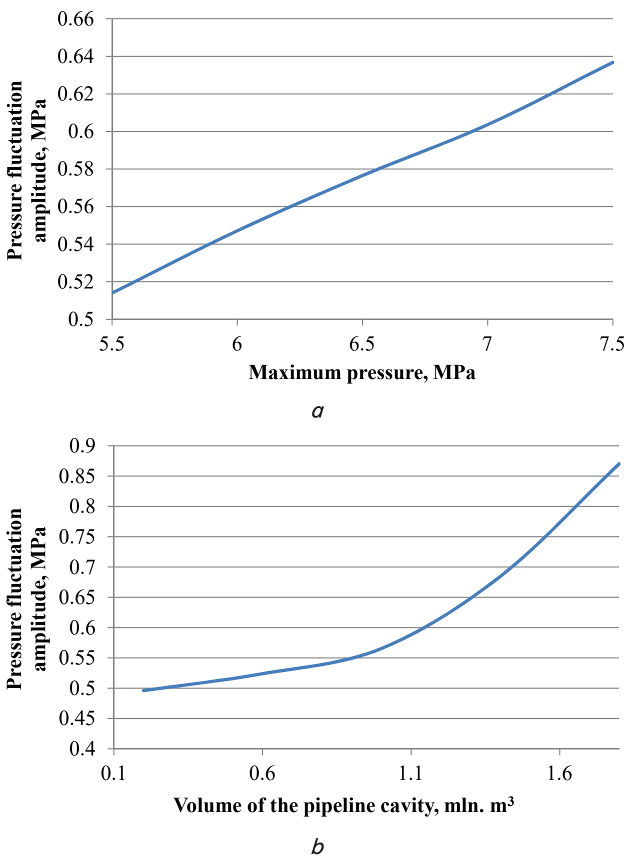


Fig. 6. Dependence of the response function on parameters: *a* — pressure P_{max}; *b* — volume V

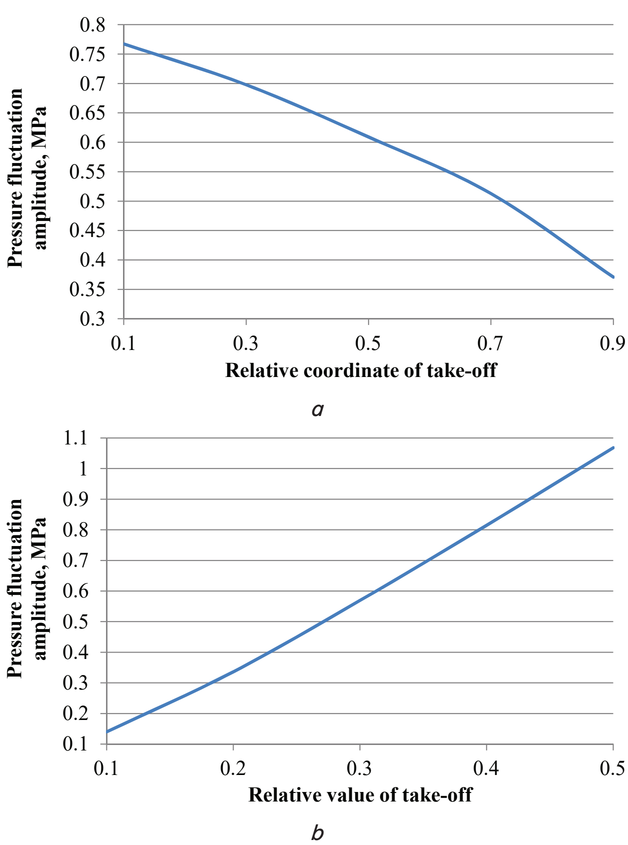


Fig. 7. Dependence of the response function on parameters: *a* — take-off coordinates x/L; *b* — amount of take-off q/Q

6. Discussion of the results obtained in the study of nonstationary processes in incompletely loaded gas pipelines

In conditions of incomplete loading of the gas-transport system [16], periodic change of productivity in order to ensure specified volumes of gas transportation should be considered the main reasons for non-stationarity. In this case, the establishment of the duration of the nonstationary process and the amplitude of pressure fluctuations are important technological problems.

Analysis of the study results shows that with a sudden change in the gas flow, the pressure wave propagates at the speed of sound to the initial section of the pipeline where pressure is maximum. An oscillating process occurs with its amplitude and frequency gradually increasing and reaching maximum values after 4–6 oscillation periods after which the process amplitude and frequency begin to decrease. The total duration of the oscillating process with high values of amplitude and frequency is in the range of 50–60 s which is considered a short-term overload of the pipeline. Amplitude and frequency of pressure fluctuations get significantly reduced with time and the oscillating process completely extinguishes in 1,800–2,100 s transferring the pipeline operation to a new stationary mode.

Series of calculations performed according to the proposed mathematical model have made it possible to establish a number of patterns of behavior of the oscillatory process caused by an abrupt change in the gas flow rate. In particular, it was found that with a decrease in operating pressure in the pipeline, the total duration of both the high-frequency range of the oscillating process and the nonstationary process, as a whole, increases, and the frequency and amplitude of oscillations decrease. For example, when working pressure is reduced from 7.5 MPa to 7 MPa (6.7 %), the maximum amplitude of pressure fluctuations decreases from 0.199 MPa to 0.18 MPa (9.5 %). When the working pressure is reduced to 6.5 MPa (13.3 %), the decrease in the amplitude of pressure fluctuations measures 34.7 %. The maximum frequency of the oscillating process is 0.44 Hz at an operating pressure of 7.5 MPa and when pressure is reduced to 7 MPa, it decreases by 21.8 %. With a further decrease in pressure to 6.5 MPa, it decreases by 39.4 %. From a physical point of view, this pattern is explained by a decrease in elasticity of the medium of oscillating waves which leads to a decrease in speed of perturbations and, as a consequence, an increase in the duration of the nonstationary process and its high-frequency band.

Linear coordinate of concentrated gas take-off has a significant effect on the behavior of the nonstationary process, in particular, on the magnitude of the pressure fluctuation amplitude and frequency. With an approach of the point of concentrated take-off to the initial section of the linear section where stationary pressure is maximum, the amplitude of the pressure fluctuation increases and frequency decreases. If the concentrated gas take-off is in the middle of the linear section of the gas pipeline, the maximum amplitude of pressure fluctuations at its beginning is 18.3 % less than in the case when the concentrated take-off is in the initial section of the gas pipeline. If the concentrated gas take-off is shifted to the final part of the linear section, amplitude reduction will approach 48.5 % at other conditions being identical. The frequency of the oscillating process varies in a smaller range. For example, frequency increase measures 7.2 % in the first case (concentrated gas take-off is in the middle of the linear section) and 11.4 % in the second case (concentrated take-off is at the end of the linear section).

The change in the speed of sound affects the behavior of pressure fluctuations in the nonstationary process caused by an abrupt change in gas flow rate to a lesser extent and the increase in the speed of sound leads to an increase in amplitude and frequency of oscillations. When the speed of sound increases from 400 m/s to 440 m/s (10 %), the increase in amplitude is 5.7 %, and the frequency is 3.1 %. When the speed of sound increases to 480 m/s (20 %), amplitude increases by 8.5 %, and frequency increases by 4.9 %.

The magnitude of the concentrated gas take-off has the greatest effect on the magnitude of amplitude and frequency of the pressure fluctuations at the beginning of the linear section of the gas pipeline in the nonstationary process caused by the abrupt change in gas flow rate. If the abrupt flow rate of concentrated take-off is 10 % of the total gas flow rate in the pipeline under stationary conditions, the maximum amplitude of pressure fluctuations in the nonstationary process caused by a sudden appearance of leakage will be 0.154 MPa. When the flow rate of concentrated take-off increases to 20 %, the amplitude of pressure fluctuations increases to 0.287 MPa, i.e. 2.45 times.

If the flow rate of concentrated take-off will be 30 % of the total gas flow rate in the pipeline under stationary conditions, the amplitude of pressure fluctuations will be 0.517 MPa, i.e. 3.55 times increase. With an abrupt increase in the flow rate of concentrated take-off to 50 % of the gas flow rate in the pipeline, the amplitude of pressure fluctuations will be 1.14 MPa. This can pose a threat to safe pipeline operation because of a short-term overload.

The maximum frequency of pressure fluctuations in the nonstationary process decreases with an increase in the flow rate of concentrated take-off. When the flow rate of concentrated take-off increases from 10 % to 20 % of the gas flow rate in the pipeline, the maximum frequency of pressure fluctuations decreases by 5.8 %. With a further increase in the flow rate of concentrated take-off to 30 % of the gas flow in the pipeline, reduction of the maximum frequency of pressure fluctuations measures 12.3 %.

A shutdown of individual CS to regulate the performance of the pipeline leads to a nonstationary process. To study this process, a mathematical model was constructed. It takes into account the increase in pressure on the compressor stations and the frequency of their startup or shutdown. The difference between the applied model and the existing ones consists in that this model takes into account friction losses and inertial energy losses. The increase in pressure on the CS was modeled using the Dirac source function.

Note that when modeling the mode of CS operation, it was assumed that the increase in pressure is the same at all stations and does not depend on the gas flow rate. In fact, the degree of pressure buildup on the CS is related to the gas flow rate by the equation of characteristics of the gas pumping unit. However, this dependence should contain both speed of rotation of the unit rotor and the scheme of their operation as parameters that would greatly complicate the model.

Thus, this model can be used to forecast modes of operation of long complex gas-transport systems. Implementation of the proposed model for conditions of the trans-Ukrainian gas pipeline system has made it possible to obtain new patterns of operating modes.

Analysis of graphical dependences of fluctuation of mass gas flow rate at the beginning ($x=0$) and the end ($x=L$) of the gas-transport system has made it possible to determine the duration of the nonstationary process caused by the gradual shutdown of each of the compressor stations. Note that nonstationary processes in gas pipelines are unprofitable in terms of energy consumption for media transportation as they cause inertial forces in a flow of a continuous medium. Their work leads to a decrease in overall system efficiency. Therefore, a mode for which the duration of the nonstationary process is minimal should be considered the most advantageous mode (other conditions being identical).

As shown by calculations of implementation of the given mathematical model, the greatest duration of the nonstationary process was characteristic of the shutdown of Borova CS-2 measuring 12,252 s (3 hours 24 minutes 12 seconds) at the beginning of the gas-transport system (at the exit of Novopskov CS) and 13,316 s (3 hours 42 minutes) at the route end. Therefore, the duration of the nonstationary process is 30.6 % longer at the end of the system than at the beginning. This is explained by the large distance between the shutdown CS to the route end. When Borova CS was shut down, the productivity of the new stationary mode was 22.5 % less than throughput (it was 675 kg/s with all operating CS).

When Khust CS was shut down (it is the second compressor station from the route end), the duration of the nonstationary process was the shortest measuring 9,180 s (2 hours 33 minutes) at the beginning of the gas-transport system and 8,123 s (2 hours 15 minutes 23 seconds) at the route end. Duration of the nonstationary process at the system beginning was 11.3 % longer than at the route end which is explained by the difference in distances from the shutdown CS to the pipeline ends. The reduction of the pipeline productivity compared to the throughput was 7.6 %.

Therefore, the duration of the nonstationary process caused by CS shutdown decreases at the beginning and end of the pipeline with increasing the number of the shutdown station. At the pipeline beginning, the tendency to productivity decrease has a more gentle sloping character than at the end. When CS-2 was shut down, the ratio of the duration of the nonstationary process at the end of the route to the corresponding duration at the pipeline beginning was 1.306. This ratio was 1.022 when the CS-5 was shutdown and 0.935 when the CS-10 was shutdown. This fact should be taken into account when forecasting regulation of operation modes of the gas-transport system through the shutdown of individual compression stations for an uninterrupted supply of gas to consumers.

The results of the studies conducted on the basis of mathematical modeling have allowed us to establish patterns of nonstationary processes in long-distance gas-transport systems with a large number of compressor stations. In particular, it was proved that the duration of the nonstationary transient mode is significantly affected by the location of the shutdown compressor stations on the pipeline route. The larger the serial number of the system CS the larger duration of the nonstationary process and the smaller magnitude of decrease in productivity.

In a case of incomplete loading of the system, superposition of pressures at the top limit line of depression can lead to exceeding the initial pressure. Therefore, to prevent pipeline overload, the initial pressure should be reduced to some extent relative to the maximum pressure. For this purpose, an empirical dependence was obtained which makes it possible to determine the value of maximum pressure with an error not exceeding 3.5 % for the operating pressure range of 7.5–5 MPa.

7. Conclusions

1. Based on mathematical modeling of nonstationary processes of the gas-transport system operating in conditions of the partial load, it was established that the range of amplitude of pressure fluctuations in the initial section of the pipeline can reach 1 MPa. As a result, there is a risk of short-term overloading of the pipeline which can lead to disruption of its trouble-free operation.

2. Implementation of the mathematical model has made it possible to establish patterns of the process of pressure fluctuations and the influence of technological parameters on the amplitude and frequency of oscillations. An empirical dependence of the maximum amplitude of pressure fluctuations on characteristics of the gas pipeline and mode parameters was proposed which makes it possible to control the safe operation of the gas-transport system under conditions of its incomplete loading.

3. The results of analytical studies have made it possible to establish patterns of nonstationary processes in lengthy gas-transport systems with a large number of compressor stations. In particular, it was proved that the duration of the nonstationary transient mode is significantly affected by the location of the shutdown CS on the pipeline route, and the larger its serial number in the system the shorter duration of the nonstationary process and smaller magnitude of productivity decrease.

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