Non-stationary processes in the gas transmission systems at compressor stations shut-down

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Abstract

There are presented results of analytical studies of the nature and duration of non-stationary processes in complex gas transmission systems caused by the shut-down mode of individual compressor stations. A mathematical model of the gas pipeline has been made, taking into account the influence of compressor stations on the basis of classical gas flow and continuity equations using the Dirac source functions. Realization of the created mathematical model by application of the Fourier and Laplace integral transforms allowed to obtain a dependence in the analytical form, reflecting the nature of the oscillation in time of the mass flow of gas in the initial and final sections of the gas pipeline. The constructed graphical dependences of the trend in the performance of the gas transportation system at its beginning and at the end showed the effect of placing the compressor station in the gas transportation system, in particular its serial number on the route number, on the nature of the non-stationary process caused by its stop, in particular, the duration of non-stationarity. The results obtained and the final conclusions will be useful in forecasting the operating modes of gas transmission systems, especially when they are not fully loaded.

Keywords: *compressor station, gas transportation system, non-stationary process.*

The gas pipeline as a unified power system is characterized not only by the cost of energy for driving gas pumping units, but also by large volumes of transportation of the medium, which in its turn is an energy carrier. The increase in the length of the gas pipeline requires an increase in the number of compressor stations (CS), which leads to an increase in the energy consumption for transportation or reduction of the energy supply to the consumer, which will lead to an increase in the specific energy consumption for transportation. Therefore, with an increase in the length of the gas pipeline, the energy cost of the gas pumped is conditionally reduced. This effect can be assessed by implementing a mathematical model of a gas pipeline created with consideration for the energy intensity of compressor stations and energy losses in linear sections [1–7].

It should be noted that according to the draft, the flow of gas by gas pipelines is considered stationary. Manifestations of nonstationarity caused by disturbances in the form of changes in the intake or withdrawal of gas from the system, as well as by fluctuations in pressure, lead to the occurrence of energy losses as a result of inertial forces, reducing the efficiency of the system. It should be noted that energy dissipation is global in nature for gas transmission systems of a large extent due to inertial forces and it creates an imaginary effect of unauthorized removal of gas from the pipeline [1, 10]. If there is a sudden increase in gas extraction at the end of the gas transportation system of a considerable extent, and a stepwise growth of gas supply to the gas pipeline at its beginning, then the propagation wave of the pressure disturbance will move with the speed of sound in the gas, and the duration of its passage is $\tau = L/c$. For the gas transportation system of Ukraine this time is about one hour. The mass flow of gas will vary in the pipes in proportion to the linear velocity of the gas, which is within 7–12 m/s. Therefore, the time of gas flow rate change in the Ukrainian system presumably amounts to 56 hours. As a result, a wave of reduced pressure moves along the gas pipeline, starting from the end, where a spasmodic growth of the withdrawal occurs, and it creates the effect of unauthorized withdrawal, which was repeatedly noted in practice [4, 8].

Under conditions of incomplete loading of the gas transportation system, its productivity can be substantially lower than the capacity. In such conditions, the problem arises of optimal regulation of the operating conditions of the system by the criterion of the minimum energy consumption for gas transportation. One of the options for regulation is the shut-down of individual compressor stations. As shown in [9], depending on the number and serial numbers of operating stations, it is possible to achieve the required productivity of the gas transportation system. At the same time, taking into account the low efficiency of gas-pumping units with a gas-turbine drive, disconnection of individual compressor stations can be an effective method of regulating productivity from the energy point of view. Obviously, such a control method can be applied for seasonal capacity control, and it

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should be borne in mind that the shut-down and restart of the compressor requires additional energy costs.

From a technological point of view, the shut-down and restart of the compressor station leads to the emergence of an unsteady process, the duration of which should be predicted in order to provide consumers with gas.

Summarizing the above, it should be concluded that it is necessary to predict non-stationary processes in complex gas transmission systems of a large extent, including a significant number of compressor stations.

Forecasting and analysing of these production situations at the gas transportation system, as well as the assessment of energy losses, are possible only on the basis of a mathematical model. Such a model is made based on the equations of nonstationary gas flow in pipes taking into account the increase in pressure at compressor stations and the continuity of the flow [2]

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

where *P(x,t)* is pressure in the gas pipeline as a function of the linear coordinate *x* and time *t;* ΔP_{CSi} is the increase of pressure at the compressor station with a coordinate x_i; $\delta(x-x_i)$ is the function of the Dirac source, simulating the increase in pressure at the compressor station, ρ is the density of the gas; *w* is the linear velocity of the gas; *d* is internal diameter of the gas pipeline; λ is the coefficient of hydraulic resistance.

Note that in order to simulate wave damping processes in a gas pipeline, the equations of motion include inertial hydraulic losses and friction losses.

The system of differential equations (1) is reduced to the equation as follows

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

where $\delta^*(x-x_i)$ is a linear derivative of the Dirac function along a linear coordinate; c is the speed of sound in the gas; $2a$ is the coefficient of linearization of the equation of motion [3]

$$2a=\frac{\lambda w}{2d}.$$

Let the gas transportation system of length *L* contain *m* intermediate compressor stations, which start to operate simultaneously at the time *t = 0*, and let the station with the number *k* be excluded from the work at t_1 moment of time. For such a case, the equation (2) will have the following form

$$\frac{\partial^2 P}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2}+\frac{2a}{c^2}\frac{\partial P}{\partial t}+\sum_{i=1}^{m}\Delta P_{CSi}\delta^*(x-x_i)+ +\Delta P_{CSk}\delta^*(x-x_k)[\sigma(t)-\sigma(t-t_1)], \quad (3)$$

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

We assume that the gas pipeline was stopped at the initial point in time and a constant pressure P_o was maintained throughout it. Then the initial conditions are

$$t=0,\quad P(x,0)=P_0,\quad \frac{\partial P}{\partial x}=0.$$

Starting from the moment of time $t>0$, a constant pressure $P(0,t)=P_{init}$ is maintained at the beginning of the gas pipeline, and a constant pressure $P(L,t)=P_{fin}$ – at the end.

To solve the mathematical model, integral transforms were used, in particular: the sine Fourier transform and the Laplace transform [2]

$$P_f=\frac{2}{L}\int_0^L P(x,t)\sin\left(\frac{\pi nx}{L}\right)dx,\quad P_l=\int_0^\infty P_f e^{-st}dt. \quad (4)$$

The solution (3) in the area of picture has the form

$$P_l=P_{f0}\left(\frac{s+2a}{s^2+2as+\left(\frac{\pi nc}{L}\right)^2}\right)+ +\frac{2\pi nc^2}{L^2}\left[P_{init}-(-1)^n P_{fin}+\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{CSi}\cos\left(\frac{\pi nx_i}{L}\right)+ +\Delta P_{CSk}\cos\left(\frac{\pi nx_k}{L}\right)\right]\frac{1}{s\left(s^2+2as+\left(\frac{\pi nc}{L}\right)^2\right)}- -\frac{2\pi nc^2}{L^2}\Delta P_{CSk}\cos\left(\frac{\pi nx_k}{L}\right)\frac{e^{-st_1}}{s\left(s^2+2as+\left(\frac{\pi nc}{L}\right)^2\right)}. \quad (5)$$

Having applied the inverse Laplace transform to (5), we obtain

$$P_f=C_n e^{-at}f(n,t)+A_n- -\frac{2}{\pi n}\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{CSi}\cos\left(\frac{\pi nx_k}{L}\right)[1-e^{-a(t-t_1)}f(n,t-t_1)]\sigma(t-t_1), \quad (6)$$

where:

$$C_n=\frac{2}{\pi n}P_0\left[1-(-1)^n\right]-A_n,$$

$$A_n=\frac{2}{\pi n}\left[P_{init}-(-1)^n P_{fin}+\sum_{i=1}^{m}\Delta P_{CSi}\cos\left(\frac{\pi nx_i}{L}\right)\right],$$

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

Having applied the inverse Fourier transform to (6) in the following form

$$P=\sum_{n=1}^{\infty}P_f\sin\left(\frac{\pi nx}{L}\right),$$

and after simple transformations, we obtain the dependence of the pressure variation of the nonstationary process in the length and time in the following form

$$
\begin{aligned}
P(x,t) &= P_0 + (P_{init} - P_{fin})\frac{x}{L} + \\
&+ \sum_{\substack{i=1 \\ i\neq k}}^{m} \Delta P_{CSi} \begin{Bmatrix} \left(1-\frac{x}{L}\right) & if \quad x > x_i \\ \left(-\frac{x}{L}\right) & if \quad x < x_i \end{Bmatrix} + \\
&+ \Delta P_{CSk}[\sigma(t) - \sigma(t-t_1)] \begin{Bmatrix} \left(1-\frac{x}{L}\right) & if \quad x > x_i \\ \left(-\frac{x}{L}\right) & if \quad x < x_i \end{Bmatrix} + \\
&+ \sum_{n=1}^{\infty} C_n e^{-at} f(n,t) \sin\left(\frac{\pi n x}{L}\right) + \\
&+ \frac{2}{\pi}\Delta P_{CSk} \sum_{n=1}^{\infty} \frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right) e^{-a(t-t_1)} f(n,t-t_1)\sigma(t-t_1).
\end{aligned}
\tag{7}
$$

The first four summands of the solution (7) characterize the stationary operation mode of the gas transport system. The fifth summand describes a nonstationary process caused by the simultaneous activation of all compressor stations at point in time $t = 0$. The last summand models a non-stationary process caused by the shut-down of the *k*-th compressor station, starting from the time point t_1. If we consider $t_1 >> 0$, that is, we consider the process in the gas pipeline after a considerable time interval from the moment of switching of all the CSs, then the initial nonstationarity will not have any effect on the process due to the higher order of smallness of the factor e^{-at}, and the solution of the problem of shut-down of the *k*-th compressor station can be represented in the form

$$
\begin{aligned}
P(x,t) &= P_0 + (P_{init} - P_{fin})\frac{x}{L} + \\
&+ \sum_{\substack{i=1 \\ i\neq k}}^{m} \Delta P_{CSi} \begin{Bmatrix} \left(1-\frac{x}{L}\right) & if \quad x > x_i \\ \left(-\frac{x}{L}\right) & if \quad x < x_i \end{Bmatrix} + \\
&+ \frac{2}{\pi}\Delta P_{CSk} \sum_{n=1}^{\infty} \frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right) e^{-a(t-t_1)} f(n,t-t_1)\sigma(t-t_1).
\end{aligned}
\tag{8}
$$

Solution (8) describes the nonstationary process caused by the shut-down of the *k*-th compressor station and does not take into account the effect of nonstationarity of the initial process of starting all the CSs. Therefore, the time countdown can be started from the moment of stop of the *k*-th compressor station. In this case we obtain

$$
\begin{aligned}
P(x,t) &= P_0 + (P_{init} - P_{fin})\frac{x}{L} + \\
&+ \sum_{\substack{i=1 \\ i\neq k}}^{m} \Delta P_{CSi} \begin{Bmatrix} \left(1-\frac{x}{L}\right) & if \quad x > x_i \\ \left(-\frac{x}{L}\right) & if \quad x < x_i \end{Bmatrix} + \\
&+ \frac{2}{\pi}\Delta P_{CSk} \sum_{n=1}^{\infty} \left[\frac{1}{n}\cos\left(\frac{\pi n x_k}{L}\right)\sin\left(\frac{\pi n x}{L}\right) e^{-at} \times \right. \\
&\left. \times \left(\cos\left(\sqrt{\left(\frac{\pi n c}{L}\right)^2 - a^2}\, t\right) + \frac{a}{\sqrt{\left(\frac{\pi n c}{L}\right)^2 - a^2}} \sin\left(\sqrt{\left(\frac{\pi n c}{L}\right)^2 - a^2}\, t\right)\right)\right].
\end{aligned}
\tag{9}
$$

Equation (9) makes it possible to predict the nature of the non-stationary process in extended gas transmission systems with a large number of compressor stations, caused by the shut-down and re-start of one of the stations.

To estimate the duration of the nonstationary process, it is necessary to construct the time dependence of the mass flow of gas, as the most inertial characteristic, at the initial or final cross section of the gas pipeline [3].

To this end, we use the equation of motion of the gas from system (1). Obviously, for the initial *(x* = 0) or a finite cross section (*x=L*), the Dirac delta function is $\delta(x - x_i) = 0$, therefore

$$
-\frac{\partial P}{\partial x} = \frac{\partial(\rho w)}{\partial \iota} + \frac{\lambda \rho w^2}{2d}. \tag{10}
$$

To simplify the computational process, we neglect inertial losses in the initial and final sections, that is, we take $\frac{\partial(\rho w)}{\partial \iota} = 0$ [2]. This, of course, is connected with a certain error in calculating the mass flow rate of gas, however, in forecasting calculations, it is not the absolute value of the flow rate of gas that is important, but the dynamics of its change over time. In addition, we use the linearization of the equation of motion, then we get

$$
m(0,t) = -\frac{\pi d^3}{\lambda w}\frac{\partial P}{\partial x}_{|x=0}, \quad m(L,t) = -\frac{\pi d^3}{\lambda w}\frac{\partial P}{\partial x}_{|x=L}. \tag{11}
$$

Using equation (9) after differentiation we get

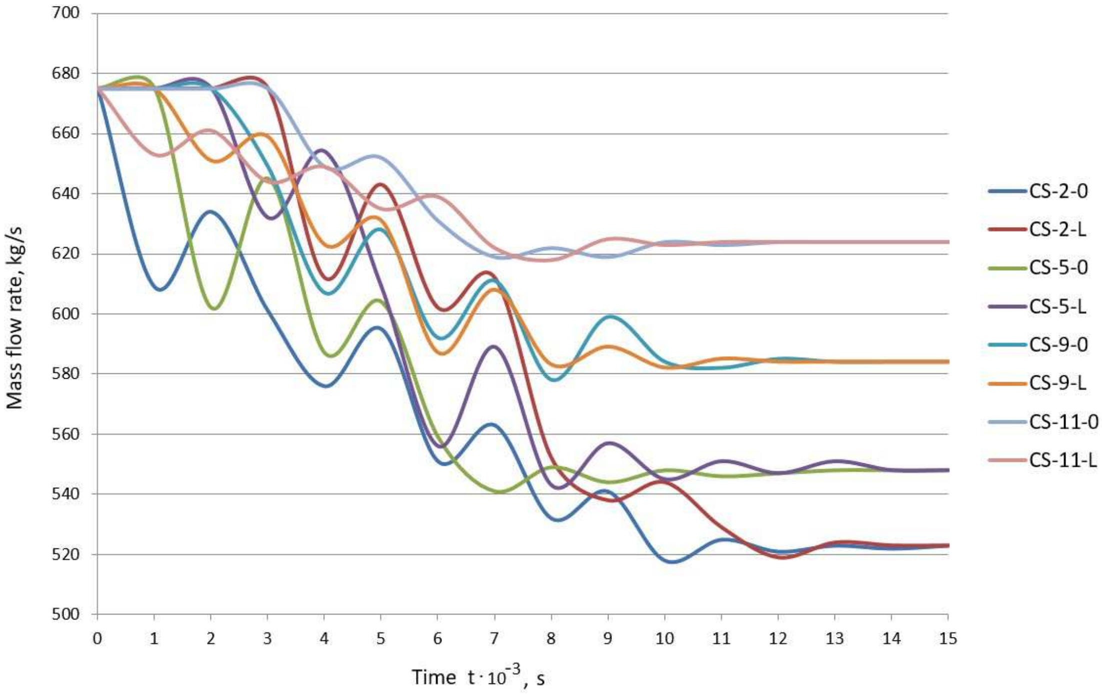

Figure 1 – The nature of the non-stationary process in the pipeline at shut-down of various compressor stations

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

(12)

$$m(L,t) = -\frac{\pi d^3}{\lambda w}\left(\frac{P_{init}-P_{fin}}{L} - \frac{\sum_{\substack{i=1\\ i\neq k}}^{m}\Delta P_{CSi}}{L} + \right.$$
$$+\frac{2L}{\pi^2}\Delta P_{CSk}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos\left(\frac{\pi n x_k}{L}\right)e^{-at}\left(\cos\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2 - a^2}\right)t + \right.$$
$$\left.\left. + \frac{a}{\sqrt{\left(\frac{\pi nc}{L}\right)^2 - a^2}}\sin\left(\sqrt{\left(\frac{\pi nc}{L}\right)^2 - a^2}\right)t\right)\right).$$

The dependences obtained allow us to predict the nature of the mass flow rate fluctuations at the beginning and at the end of the gas transmission system of a large extent, which includes *m* intermediate compressor stations caused by the shutdown or re-activation of the *k*-th compressor station ($k = 1, 2, \ldots m$).

To conduct researches on the effect of the number of a disabled compressor station on the duration of a non-stationary process, a computational experiment was conducted on the basis of the Soyuz gas pipeline with a total length of 1567.3 km (in Ukraine) with a diameter of 1420 mm and a wall thickness of 20 mm, with 13 compressor stations equipped with GTK-10I gas pumping units. Predictive calculations of non-stationary processes caused by shut-down of the compressor station will be carried out for the conditions of the design mode, according to which the capacity of the pipeline is 26 billion m^3 per year, with an initial pressure (at the outlet of the compressor station) 7.5 MPa and final (at the inlet of the compressor station 5 MPa, the station differential ΔP_{CS} = 2.5 MPa, which will be considered the same for all CSs. The initial station CS-11 Novopskov will be considered the main station, and the remaining 12 – intermediate ones. The task is to determine the nature of the pipeline capacity change over time at its beginning and in the end according to (12) for de-phased shut-down of each of the intermediate CSs.

The calculations, carried out according to the described methodology, allowed us to obtain results that are presented in the form of graphs in Figure 1.

The analysis of the graphical dependences of the mass flow rate at the beginning (x = 0) and at the end ($x = L$) of the gas transmission system made it possible to determine the duration of the non-stationary process caused by the phased shutdown of each of the compressor stations. It should be noted that non-stationary processes in gas pipelines are unprofitable from the point of view of energy consumption for pipeline transport, since they cause the appearance of inertial forces in a continuous flow, the operation of which leads to a decrease in the overall efficiency of the system. Therefore, the most advantageous mode (under other identical conditions) should be considered the mode for which the duration of the non-stationary process is minimal.

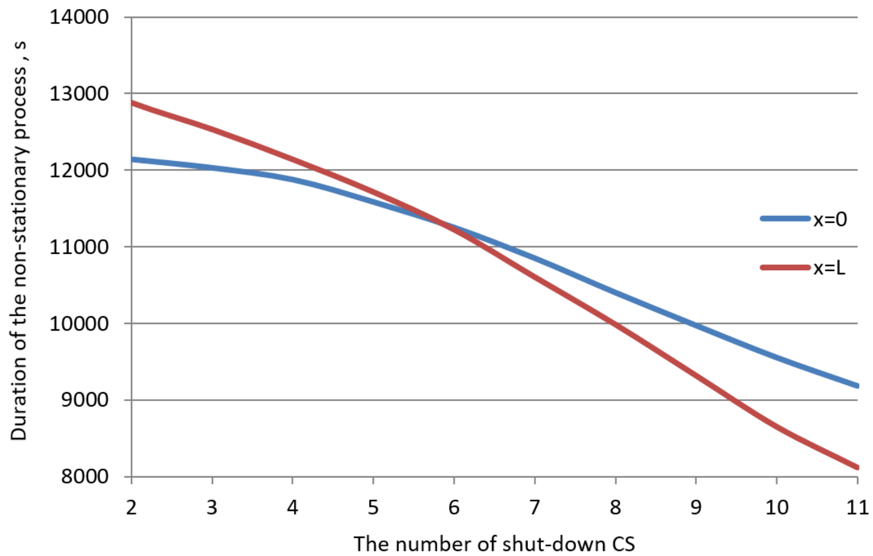

Figure 2 – Duration of the non-stationary process caused by the shut-down of compressor stations for the initial (*x*=0) and final (*x* = *L*) cross section of the gas pipeline

As shown by calculations of the above mathematical model, the longest non-stationary process is characteristic for the shut-down of CS-2 Borova and it is 12,252 s (3 h 24 min 12 s) at the beginning of the gas transmission system (at the Novopskov CS exit) and 13,316 s (3 h 42 min) at the end of the route. So, the duration of the non-stationary process at the end of the system is 30.6 % longer than at the beginning, which is explained by the significant distance from the CS stopped to the end of the route. With the shut-down of the Borova CS, the performance of the new stationary mode is less than the carrying capacity (for all the operating CSs, it is 675 kg/s) by 22.5 %.

When the Khust compressor station is shut down (the second compressor station from the end of the route), the non-stationary process is the shortest and is 9,180 s (2 h 33 min) at the beginning of the gas transportation system and 8,123 s (2 h 15 min 23 s) at the end of the route. The duration of the non-stationary process at the beginning of the system is 11.3 % longer than at the end of the route, due to the difference in distance from the stopped CS to the ends of the pipeline. The decrease in the performance of the pipeline compared to the capacity is 7.6 %.

Figure 2 shows the graphs of the duration of the non-stationary process at the beginning and at the end of the gas transmission system with a phased shut down of each of the compressor stations. As can be seen from the graphs, the duration of the non-stationary process, caused by the shutdown of the compressor station, decreases at the beginning and end of the pipeline as the number of the stopped station increases, and at the beginning of the pipeline, the tendency to decrease in productivity has a flatter character than at the end. So, when the CS-2 is shut down, the ratio of the duration of the non-stationary process at the end of the route to the corresponding duration at the beginning of the pipeline is 1.306, when the CS-5 is shut down, this ratio is 1.022, and when the CS-10 is shut down, it is 0.935. This circumstance should be taken into account when predicting the regulation of operating modes of the gas transmission system by shut-down of individual CSs for the uninterrupted supply of consumers with gas.

The results of studies based on mathematical modeling allowed to establish patterns of non-stationary processes in long gas transmission systems with a large number of compressor stations, in particular, it was proved that the duration of non-stationary transient mode is influenced by the placement of a shut down CS on the pipeline route, besides the duration of the non-stationary process and the magnitude of the production reduction are reduced with the increase of its sequence number in the system.

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Нестаціонарні процеси в газотранспортних системах призупинених компресорних станцій

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Наведено результати аналітичних досліджень характеру протікання і тривалості нестаціонарних процесів у складних газотранспортних системах, викликаних виключенням з режиму роботи окремих компресорних станцій. Побудовано математичну модель газопроводу з врахуванням впливу компресорних станцій на основі класичних рівнянь газового потоку і нерозривності з використанням функцій джерела Дірака. Реалізація створеної математичної моделі шляхом застосування інтегральних перетворень Фур'є і Лапласа дозволила отримати в аналітичній формі залежність, що відображає характер коливання в часі масової витрати газу в початковому і кінцевому перерізах газопроводу. Побудовані графічні залежності тренду продуктивності газотранспортної системи на її початку і в кінці показали вплив розміщення компресорної станції в газотранспортній системі, її порядкового номеру на трасі на характер нестаціонарного процесу, викликаного її зупинкою, зокрема, на тривалість нестаціонарності. Отримані результати будуть корисними при прогнозуванні режимів роботи газотранспортних систем, особливо за умови їх неповного завантаження.

Ключові слова: *газотранспортна система, компресорна станція, нестаціонарний процес.*