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An Iterative Method for Solving the Problem of Pipeline Transportation of Gas along a Relief Track

Bazarov Orifjon Shadiyevich,Khujaev Ismatulla Kushayevich, Ismailov Alisher Abdulxayevich

Associate Professor, Rector, Karshi engineering-economics institute, Karshi, Uzbekistan
Professor, Leading researcher, Scientific and innovation center of Information and communication technologies, Tashkent University of Information Technologies, Tashkent, Uzbekistan
Candidate of technical sciences, Teacher, Tashkent Institute of Textile and Light Industry, Tashkent, Uzbekistan

ABSTRACT.A numerical method developed to solve the problem of pipeline transport of real gas, when a pressure change in time is specified at the inlet, and a change in the mass flow of gas is output. Unlike other works, the height of the axis of the gas pipeline varies depending on the distance.

Using the new desired natural logarithm of the reduced gas density, the degree of unknowns in the momentum conservation equation reduced, according to which the directional pressure change is due to the local and convective components of the gas inertia force, the quadratic law of resistance and gravity. Using this equation and the equation of conservation of mass, the equations compiled for traveling along the stream and against the flow of waves.

For the numerical solution of the system of equations, an implicit scheme is used and the directions of propagation of the forward and backward waves are taken into account. Simple dependences are proposed to approximate the boundary condition for pressure, and to satisfy the boundary condition for mass flow, a transcendental equation is constructed with respect to the inlet flow rate. To solve the latter, a sequential approximation algorithm based on the Newton tangent method has been developed. Due to the nonlinearity of convective terms and the resistance force, an iterative process is organized for a fixed time step. As an initial condition, it is proposed to use a numerical solution of the momentum conservation equation in a stationary setting at a constant gas mass flow rate.

The results of computational experiment for various options of the route and indicators of the object are presented.

KEYWORDS.gas pipeline, force factors, laws of conservation of momentum and mass, traveling wave method, numerical method, tangent method, iteration method, computational experiment.

I. INTRODUCTION

The decrease in operating costs of the pipeline network is closely related to the increase in capital investment in its creation. Practice shows that those projects that have undergone preliminary testing in terms of economics, reliability, ecology and other indicators are supported. In the course of design work, these factors are analyzed comprehensively and at the same time, the role of mathematical modeling and computational experiment is quite significant.

In the mathematical modeling of linear networks of gas pipelines, they rely on the laws of conservation of mass, momentum and energy of the transported gas [1], which are formed in the framework of a quasi-one-dimensional approach and contain terms up to the fourth degree unknown (in the energy conservation equation). The relations closing these laws in the form of the equation of state of the real gas and the Redlich-Kwong equation also contain terms with the third degree.

Point elements of network (blowers, taps, jumpers, chokes, consumer connection points, etc.) usually lead to an abrupt change in one or more gas indicators.

Using a quasi-one-dimensional approach when compiling a mathematical model of an object allows to avoid solving problems of three-dimensional flows, but the problems are complicated due to the complicated topology of the

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gas pipeline and the factors taken into account [2,3]. The use of various models of turbulent two-phase flow, taking into account changes in the state of aggregation of the transported medium [4-6], leads to a significant complication of the tasks. Heat transfer with the environment [7-10], transients, leakage from the gas pipeline and other factors [11-18] can lead to a change in the internal structure and composition of the equations involved.

In certain intervals of indicators, superchargers [13] can work, there is a need to use a looped network [15] and other complicating elements.

The main and booster compressor stations operating in the main gas pipelines network create such a degree of compression of the transported gas that is sufficient to overcome the frictional force and deliver gas to the consumer with a pressure that is greater than the minimum allowable and necessary gas flow rate [19]. In this regard, the issues of transition to large pipeline diameters and high operating pressures in the network are relevant. Both of these factors, as the analysis of the equations show, contribute to a smaller loss of hydrostatic pressure, which is a measure of the energy consumption of the main gas pipeline network. Due to these two factors, the volume of transported gas accumulated in the network increases, which is very useful for smoothing pressure surges and short-term peaks in gas consumption without involving additional gas sources and compression tools.

Studies in the above and other works were carried out by numerical methods.

In this paper, we propose a method for solving the problem of the gas-dynamic state of a linear section of a relief main gas pipeline according to changes in time of the inlet pressure and outlet gas flow.

The equations of conservation of momentum and gas mass by introducing auxiliary functions are transformed to the equations of the forward and backward traveling waves. The obtained equations are approximated by an implicit scheme taking into account the direction of propagation of disturbances and are presented in the form of recurrence dependencies. When the boundary condition is realized in the form of a given mass flow rate, a transcendental equation for the flow velocity is compiled, which is solved by the tangent method. Because the system of equations is nonlinear, then when solving it for a fixed time, an iterative process was organized.

Separate results of a computational experiment are presented.

The task is as follows. Suppose that a gas main with a length of $l$laid along the route, the leveling height of $z_1(x)$ which varies with distance. The diameter of the pipeline D and the coefficient of friction λ resistance are constant, which correspond to the developed turbulent flow regime. At the inlet of the gas pipeline, the law of pressure change is set, and at the end of the section, the law of change in mass flow is set.

Considering the temperature of the transported gas to be constant, it is necessary to develop a numerical method for solving the nonlinear equations of pipeline transport of real gas.

II. SIGNIFICANCE OF THE SYSTEM

A numerical method developed to solve the problem of pipeline transport of real gas, when a pressure change in time is specified at the inlet, and a change in the mass flow of gas is output. Unlike other works, the height of the axis of the gas pipeline varies depending on the distance. The study of literature survey is presented in section III, methodology is explained in section IV, section V covers the experimental results of the study, and section VI discusses the future study and conclusion.

III. METHODOLOGY

We compose a mathematical model of the problem. The equations of conservation of momentum and mass in an elementary section of a gas pipeline with a length l and diameter D are written in quasi-one-dimensional form [1, 19, 20]:

$$\begin{cases} \rho\dfrac{\partial u}{\partial t}+\rho u\dfrac{\partial u}{\partial x}+\dfrac{\partial p}{\partial x}=-\dfrac{\lambda}{2D}\rho u^2-\rho g\,sin\alpha, \\ \dfrac{\partial \rho}{\partial t}+\dfrac{\partial \rho u}{\partial x}=0. \end{cases} \tag{1}$$

Here $\rho,\ u,\ p\ -$ cross-sectional average values of density, velocity and gas pressure in the cross section x at a time t; $\lambda\ -$ coefficient of friction in the quadratic law of resistance; $g\ -$ gravitational acceleration; $sin\alpha=\dfrac{dz_1}{dx};\ z_1=z_1(x)$ – leveling height of the pipeline axis.

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The equation of state of a real gas, taking into account the average value of the coefficient of gas compressibility *Z*, is written as [1]:

$$p = ZRT\rho = \gamma\rho, \tag{2}$$

where $R, T -$ reduced gas constant and gas temperature; $\gamma = c^2 -$ squared velocity of propagation of small pressure disturbances in a gaseous medium.

At the entrance to the site, the law of pressure change over time is set:

$$p(0,t) = p_0(t), \tag{3}$$

and at the exit from the site - the change in mass gas flow rate over time:

$$M(l,t) = M_l(t). \tag{4}$$

The mass flow rate, usually used to lower the degree of unknowns in system (1), has the form:

$$M(x,t) = f\, u(x,t)\ \rho(x,t), \tag{5}$$

where $f = \pi D^2/4 -$ cross-sectional area of a gas pipeline. D and f can have piecewise constant values and this only affects the resistance force in the equation of conservation of momentum.

Usually, the introduction of mass flow rate [2,3,19] reduces the degree of unknown in the equations of conservation of momentum and mass. At the same time, convection and resistance forces remain in the form of members with a second degree of unknowns. In this case, to lower the degree of equations, an auxiliary function was introduced [20]

$$\varphi(x,t) = \ln\frac{\rho(x,t)}{\rho_*}, \tag{6}$$

which is often used in solving linear and nonlinear problems of acoustics (here $\rho_* -$ gas density, for example, under normal conditions). In this case, equations (1), taking into account the equation of state of the real gas (2), take the form:

$$\begin{cases} \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + c^2\frac{\partial \varphi}{\partial x} = -\frac{\lambda}{2D}u^2 - g\, sin\alpha, \\ \frac{\partial \varphi}{\partial t} + \frac{\partial u}{\partial x} + u\frac{\partial \varphi}{\partial x} = 0. \end{cases} \tag{7}$$

We pass to the equations of the forward and backward traveling waves. To obtain the direct wave equation, we add the first equation with the second equation of the system (7), previously multiplied by *c*. The backward wave equation is obtained in a similar way, but the second equation of system (7) is preliminarily multiplied by *–c*:

$$\begin{cases} \frac{\partial (u + c\varphi)}{\partial t} + (u+c)\frac{\partial (u + c\varphi)}{\partial x} = -\frac{\lambda}{2D}u^2 - g\, sin\alpha, \\ \frac{\partial (u - c\varphi)}{\partial t} + (u-c)\frac{\partial (u - c\varphi)}{\partial x} = -\frac{\lambda}{2D}u^2 - g\, sin\alpha. \end{cases} \tag{8}$$

As a result, we obtain a system of equations

$$\begin{cases} \frac{\partial f_1}{\partial t} + (u+c)\frac{\partial f_1}{\partial x} = -\frac{\lambda}{2D}u^2 - g\, sin\alpha, \\ \frac{\partial f_2}{\partial t} + (u-c)\frac{\partial f_2}{\partial x} = -\frac{\lambda}{2D}u^2 - g\, sin\alpha, \end{cases} \tag{9}$$

where

$$f_1(x,t) = u(x,t) + c\varphi(x,t),\ \ f_2(x,t) = u(x,t) - c\varphi(x,t) \tag{10}$$

– new desired functions.

If the values of $f_1(x,t)$ and $f_2(x,t)$ are known, then the gas indicators are determined by the formulas

$$u(x,t) = \frac{f_1(x,t) + f_2(x,t)}{2},$$

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$$\rho(x,t)=\rho_* e^{\frac{f_1(x,t)-f_2(x,t)}{2c}},$$
$$p(x,t)=\gamma\rho(x,t).$$

The boundary conditions for the new system of equations will be returned in the course of the description of the method of numerical solution of the problem.

To solve the problem numerically, we first represent the system of equations (9) in dimensionless variables. As the scales of distance, time and flow velocity, we take the length of the section as l, the travel time of the section wave as l/c and the speed of sound are taken c. Functions $f_1(x,t)$ and $f_2(x,t)$ are become dimensionless with the involvement of c. To make the density and pressure dimensionless, the characteristic values of ρ_* and $p_*=c^2\rho_*$ are used. As the result, from (9) we obtained the system:

$$\begin{cases}\frac{\partial\bar f_1}{\partial\bar t}+(1+\bar u)\frac{\partial\bar f_1}{\partial\bar x}=-\frac{\lambda l}{2D}\bar u^2-\frac{gl}{c^2}sin\alpha,\\ \frac{\partial\bar f_2}{\partial\bar t}-(1-\bar u)\frac{\partial\bar f_2}{\partial\bar x}=-\frac{\lambda l}{2D}\bar u^2-\frac{gl}{c^2}sin\alpha.\end{cases}\quad(11)$$

Discrete coordinates i, n with constant steps τ and h, grid functions $\bar f_{1i}^n$, $\bar f_{2i}^n$, $\bar u_i^n$, $\bar\rho_i^n$, $sin\,\alpha_i$ are introduced.

An implicit scheme was used to approximate the equations. The convective terms were approximated taking into account the direction of the distribution of disturbances: $\bar f_1$ − left to right (ascending index i), and $\bar f_2$ − from right to left. The right-hand sides were taken as arithmetic mean for the nodes participating in the approximation of the convective term:

$$\frac{\bar f_{1i}^{n+1}-\bar f_{1i}^n}{\tau}+(1+\tilde u_i^n)\frac{\bar f_{1i}^{n+1}-\bar f_{1i-1}^{n+1}}{h}=\Phi_{1i}^n,$$
$$\frac{\bar f_{2i}^{n+1}-\bar f_{2i}^n}{\tau}-(1-\tilde u_i^n)\frac{\bar f_{2i+1}^{n+1}-\bar f_{2i}^{n+1}}{h}=\Phi_{2i}^n.$$

Here

$$\Phi_{1i}^n=-\frac{\lambda l}{4D}\left[(\tilde u_i^n)^2+(\tilde u_{i-1}^n)^2\right]-\frac{gl}{2c^2}\left(sin\,\alpha_i+sin\,\alpha_{i-1}\right),$$
$$\Phi_{2i}^n=-\frac{\lambda l}{4D}\left[(\tilde u_i^n)^2+(\tilde u_{i+1}^n)^2\right]-\frac{gl}{2c^2}\left(sin\,\alpha_i+sin\,\alpha_{i-1}\right).$$

The speed values highlighted in the form $\tilde u_i^n$ will be returned later. Assuming that the value $\bar f_{10}^{n+1}$ is known, the values of $\bar f_{1i}^{n+1}$ were found by the formula for $i=1...N$

$$\bar f_{1i}^{n+1}=\frac{\bar f_{1i}^n+\sigma(1+\tilde u_i^n)\bar f_{1i-1}^{n+1}+\tau\Phi_{1i}^n}{1+\sigma(1+\tilde u_i^n)},$$

where $\sigma=\tau/h$.

Similarly, considering known $\bar f_{2N}^{n+1}$, $\bar f_{2i}^{n+1}$ was calculated when $i=N-1...0$ by the formula

$$\bar f_{2i}^{n+1}=\frac{\bar f_{2i}+\sigma(1-\tilde u_i^n)\bar f_{2i+1}^{n+1}+\tau\Phi_{2i}^n}{1+\sigma(1-\tilde u_i^n)}.$$

Then we turned to determine the values of $\bar f_{10}^{n+1}$ and $\bar f_{2N}^{n+1}$.

When $\bar x=0$ condition is given $p(0,t)=p_0(t)$. Therefore $\varphi_0^{n+1}=\ln\left(p_0^{n+1}/p_*\right)$. In addition, we assume that the value of $\bar f_{20}^{n+1}=\bar u_0^{n+1}-\varphi_0^{n+1}$ is known.

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From here we find $\bar{u}_0^{n+1} = \bar{f}_{20}^{n+1} + \varphi_0^{n+1}$ and $\bar{f}_{10}^{n+1} = \bar{u}_0^{n+1} - \varphi_0^{n+1}$.

At the second end of the site, i.e. when $\bar{x} = 1$, the condition for mass flow is given:

$$f\,\rho(l,t)\,u(l,t) = M_l(t).$$

Passing to dimensionless and discrete variables, we obtain

$$\bar{\rho}_N^{n+1}\,\bar{u}_N^{n+1} = Q_l^{n+1},$$

where $\dfrac{M_l(\bar{t})}{\rho_* fc} = Q_l(\bar{t}) = Q_l^{n+1}$.

Assuming the value $\bar{f}_{1N}^{n+1} = \bar{u}_N^{n+1} - \varphi_N^{n+1}$ is known, defining $\varphi_N^{n+1} = \bar{f}_{1N}^{n+1} - \bar{u}_N^{n+1}$ and, $\bar{\rho}_N^{n+1} = e^{\bar{f}_{1N}^{n+1} - \bar{u}_N^{n+1}}$ the boundary condition is reduced to the transcendental equation

$$\bar{u}_N^{n+1}\, e^{-\bar{u}_N^{n+1}} = Q_l^{n+1}\, e^{-\bar{f}_{1N}^{n+1}}.$$

We composed an auxiliary function

$$F(\bar{u}) = Q_l^{n+1}\, e^{-\bar{f}_{1N}^{n+1}} - \bar{u}\, e^{-\bar{u}}.$$

This function, due to the negative value of the derivative

$$F'(\bar{u}) = -(1-\bar{u})\, e^{-\bar{u}},$$

monotonously decreases in its domain of definition $\bar{u} \in [0;1]$. When $\bar{u} = 0$ function $F(\bar{u})$ has a positive value, and $\bar{u} = 1$ – when negative. Accordingly, the equation has a unique solution. And we can find it by the Newton tangent method.

The tangent passing through the point $(\bar{u}_N^k, F(\bar{u}_N^k))$ where $k = 0, 1, 2 ...$ – the ordinal number of approximation and $u_N^0 = 0$ has an angular coefficient

$$F(\bar{u}_N^k) = \frac{F(\bar{u}_N^{k+1}) - F(\bar{u}_N^k)}{\bar{u}_N^{k+1} - \bar{u}_N^k}.$$

Because when $\bar{u} = \bar{u}_N^{k+1}$ the curve $F(\bar{u})$ crosses the abscissa axis, i.e. $F(\bar{u}_N^{k+1}) = 0$, then for $\bar{u}_N^{k+1}$ we obtain the formula

$$\bar{u}_N^{k+1} = \bar{u}_N^k + \frac{Q_N^{n+1}\, e^{\bar{u}_N^k - \bar{f}_{1N}^{n+1}} - \bar{u}_N^k}{1 - \bar{u}_N^k}.$$

The refinement process continues until at least one of the conditions $\left|F(\bar{u}_N^{k+1})\right| < 10^{-10}$ and $\left|\bar{u}_N^{k+1} - \bar{u}_N^k\right| < 10^{-8}$. Because $\bar{f}_{1N}^{n+1}$ and $\bar{u}_N^{n+1}$ are known, then we calculate the missing elements: $\varphi_N^{n+1} = \bar{f}_N^{n+1} - \bar{u}_N^{n+1}$, $\bar{f}_{2N}^{n+1} = \bar{u}_N^{n+1} - \varphi_N^{n+1}$.

Let us return to the notation $\tilde{u}_i^n$ that was used in approximating the equations for $\bar{f}_1$ and $\bar{f}_2$ as well as their right-hand sides. It means the value of the dimensionless flow rate of the previous m-approximation, $\bar{u}_i^{n+1}$, $\bar{f}_{1i}^{n+1}$, $\bar{f}_{2i}^{n+1}$ and φ_i^{n+1}. mean the values of the present $m+1$ approximation of the sought. In the zeroth approximation $\tilde{u}_i^n$ taken from the results n - time layer, and in subsequent $m+1$ approximations $\tilde{u}_i^n$ taken from previous m - approximation $n+1$ - time layer. A consistent approach is considered achieved while fulfilling the conditions $\max_{i=0..N}\left|\tilde{u}_N^n - \bar{u}_N^{n+1}\right| < \varepsilon_u$ and $\max_{i=0..N}\left|(\varphi_i^{n+1})^m - (\varphi_i^{n+1})^{m+1}\right| < \varepsilon_\varphi$. After that, we can go to the next $(n+1)$ st time layer.

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It is proposed to determine the initial condition of the problem from the first equation of system (1), which for $\frac{\partial u}{\partial t}=0$ (i.e., when passing to the stationary equation) takes the form:

$$\frac{dp}{dx}+\frac{d\rho u^2}{dx}+\frac{\lambda}{2D}\rho u^2+\rho g\, sin\alpha=0.$$

Assuming a constant mass flow rate at $t=0$

$$M(x,0)=f\,u(x,0)\;\rho(x,0)=const$$

using the gas equation of state, the last equation is reduced to a dimensionless form [3]

$$\frac{d\overline{p}}{d\overline{x}}=\frac{\overline{G}\sin\alpha\,\overline{p}^3+\overline{\Lambda}\overline{p}}{\overline{\mathrm{A}}-\overline{p}^2},$$

where $\overline{G}=\frac{gl}{\gamma}$, $\overline{\Lambda}=\frac{\lambda\gamma l M_0^2}{2Df^2p_*^2}$, $\overline{\mathrm{A}}=\frac{\gamma M_0^2}{f^2p_*^2}$.

Integrating this equation under the condition $\overline{p}(0,0)=\overline{p}_0^0$ numerically

$$\overline{p}_{i+1}^0=\overline{p}_i^0+h\frac{\left(\overline{G}\sin\alpha_i(\overline{p}_i^0)^2+\overline{\Lambda}\right)\overline{p}_i^0}{\overline{\mathrm{A}}-(\overline{p}_i^0)^2},$$

we find the values of dimensionless pressure in the computational nodes $i=1..N$. Next, we calculate

$\varphi_i^0=ln\left(\overline{p}_{i+1}^0\right)$, $\overline{u}_i^0=\frac{M_0}{f\rho_* c}\frac{1}{\overline{p}_i^0}$ at $i=0..N$. According to them, the values of

$f_{1i}^0=\overline{u}_i^0+\varphi_i^0$, $f_{2i}^0=\overline{u}_i^0-\varphi_i^0$. are calculated.

IV. EXPERIMENTAL RESULTS

Based on the presented algorithm, a calculation program was developed and a computational experiment was conducted for various options for the values of inlet pressure, outlet mass flow rate, and site performance.

The dimensionless steps amounted to $\tau=0.0002$ and $h=0.001$. The main calculations were carried out for $l=20.0$ km, $p=5.6$ MPa and $M_0=250.0$ kg/s. The choice of such a section length is justified by the fact that at large distances the friction force prevails, and at small distances, the components of the inertia of the gas, when it is possible to simplify the equation of conservation of momentum, we discard minor terms.

As constant calculation took $\lambda=0.028$, $T=300.0\ K$, $Z=0.92$, $c=378.21$ m/s. Reduced gas constant R_0 took for methane.

Track profiles were taken linear: horizontal ($\sin\alpha=0.0$), with positive slope ($\sin\alpha=0.1$), negative slope ($\sin\alpha=-0.25$) and, unlike [20], the curved path according to Fig. 1.

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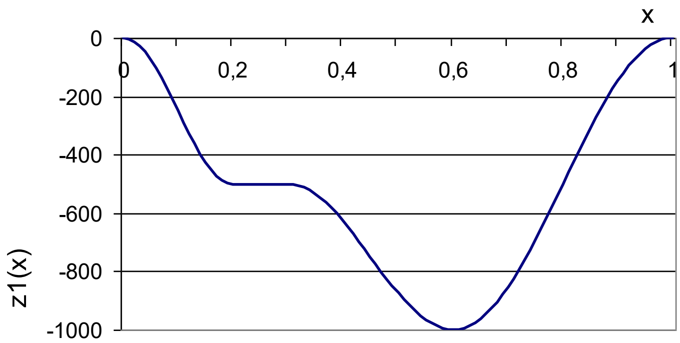

Fig. 1. The profile of the curved path depending on dimensionless distance x at greatest depth H=1000 m.

The initial pressure distribution in the stationary flow regime at $p = 5.6$ MPa and $M_0 = 250.0$ kg/s for four route options are shown in Fig. 2. The top line corresponds to the case $\sin\alpha = -0.25 = const$. According to [3], with significant negative slopes of the path, a "post-passage" mode is formed when the potential energy of gas gravity compensates for the friction forces, and the excess energy of the gravitational force is accumulated in the form of potential gas compression energy. In other words, downstream pressure is increasing.

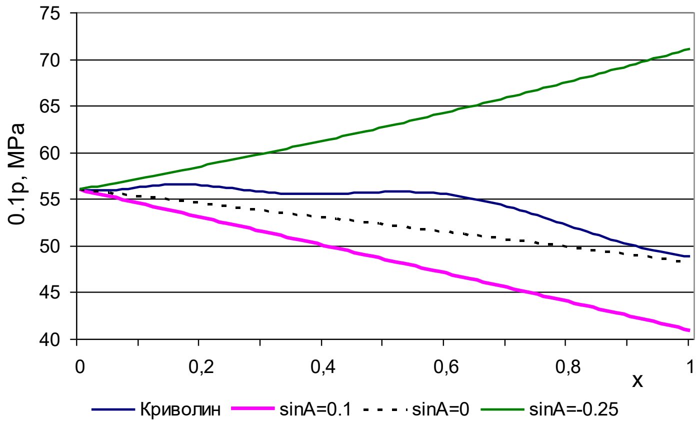

Fig. 2.Initial pressure distributions for four route options. $l = 20.0$ **km,** $p = 5.6$ **MPa and** $M_0 = 250.0$ **кg/s,** $\lambda = 0.028$, $T = 300.0\ K$, $Z = 0.92$, $c = 378.21$ **m/s.**

The lower curve corresponds to a constant positive slope of the track $\sin\alpha = 0.1$. In this case, the pressure loss in the section will be greater than in the horizontal section, i.e. at $\sin\alpha = 0.0$ (bottom second line).

The total pressure loss in the curved path (the second curve from the top) and in the horizontal path is approximately the same. In a curved path, the pressure curve is not monotonic. With a decrease in the height of the axis of the gas pipeline (at $0 \le \bar{x} \le 0.2$) pressure begins to increase. In a horizontal section (at $0.2 \le \bar{x} \le 0.3$) the pressure curve is parallel to the pressure curve obtained at $\sin\alpha = 0.0$. When lifting the track (at $0.6 \le \bar{x} \le 1$) the pressure drops more intensively, since in this section energy is additionally spent on lifting gas along the route.

We confine ourselves to presenting the results of the case when $p = 5.6$ MPa, $M_0 = 250.0$ kg/s and $M(l,t) = 300.0$ kg/s, when the intensity of gas extraction from the end of the curved section increases by 20%. The Figure 3 shows the mass flow isolines with an interval of 5 kg / s up to the time $t = 3l / c$.

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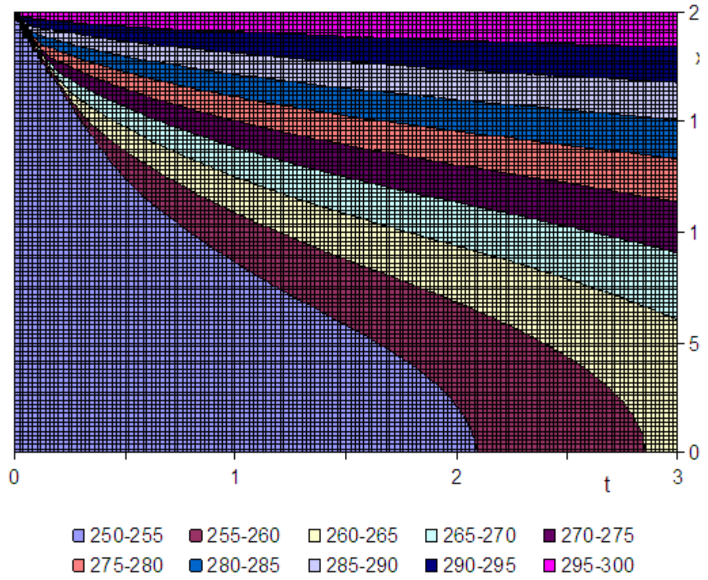

Fig. 3. The mass flow isolines in a curved section in time interval $(0;3l/c)$***. Data see fig. 2***

Reconfiguration of the mass flow begins at the end of the section where there was an instant increase in mass flow. The mass flow jump begins to move upstream with a velocity of *c*. Therefore, the mass flow isolines at the point $(0;\ 20)$ have a common tangent. This means that at small distances the influence of the friction force is still insignificant. At $t=l/c$, those. at $\overline{t}=1$, given at $\overline{t}=0$ at the end of the section, the mass flow jump reaches the inlet section $\overline{x}=0$. At $t=0.3l/c$ the deviation of isolines from the wave line of the mass flow jump is already observed.

Shown in fig. 3 isolines of the mass flow rate of gas display the picture before time $t=3l/c\approx 159$ seconds. Before reaching the disturbances of the beginning of the section with respect to the hydrodynamic flow velocity, a time equal to $l/u_{cp}\approx 2000$ seconds, and to establish the mode to a homogeneous mass flow of gas in the area $M(\tilde{o},t)=300.0$ кg/s it takes several times more than this time.

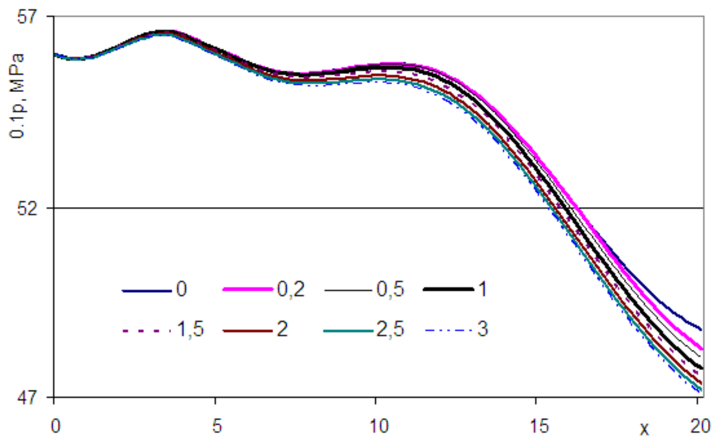

Fig. 4. Pressure plots along the length of the curved section at different values of dimensionless time. Data see fig. 4.

Fig. 4.shows pressure plots for different dimensionless calculation times. They indicate that before reaching the beginning of the plot, pressure perturbation graphs have common parts that contract over time (the top four curves). The increase in gas mass flow at the end of the section leads to a decrease in pressure with the expiration of time,

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starting from the end of the section. But the general nature of the graphs, associated with the relief of the track, remains valid.

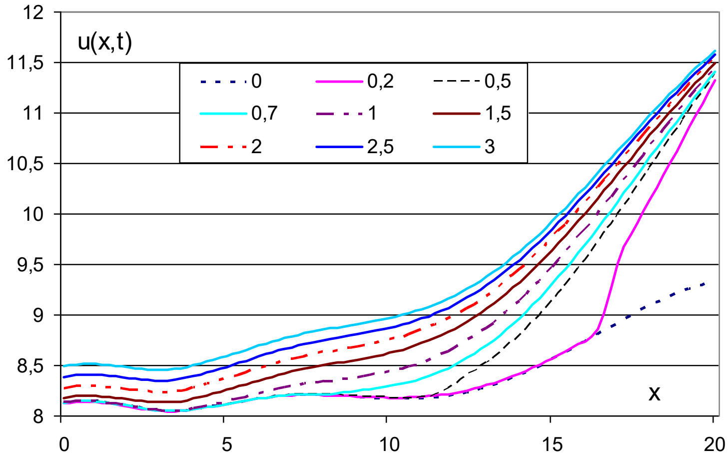

Fig. 5.The distribution of flow velocity along the length of the section of 20 km at various values of dimensionless time. Data see fig. 3.

We present the velocity plots for the case under consideration (Fig. 6). According to the object model, the flow rate is inversely proportional to hydrostatic pressure. The bottom curve in fig. 6.corresponds to the second from above pressure curve in the stationary case: an increase in the pressure graph (Fig. 3.) leads to a decrease in the flow velocity (Fig. 6.) and vice versa. In this case, the propagation of the jump in mass flow formed at the end of the section is more pronounced.

The second curve below, which is built for $\overline{t} = 0.2$, determines an abrupt increase in flow velocity at the end of the section. This curve for $\overline{x} = 0.2$ closes with the initial velocity curve, i.e. at $\overline{t} = 0.2$ the wave reaches the cross section $\overline{x} = 0.2$. At $\overline{t} = 0.5$ the wave reaches almost half the length of the section (the third curve from the bottom), but it is significantly deformed due to the friction force and gas compressibility.

In general, there is a restructuring of the gas-dynamic parameters of the site, which leads to a stationary case with a constant mass flow $M(x,t) = 300.0$ кg/s.

Similar results, but with smoother transitions, were obtained for straight-line gas pipeline routes with $\sin\alpha = 0.0$, $\sin\alpha = 0.1$and $\sin\alpha = -0.25$ at various values of inlet pressure and outlet mass flow rate of gas.

Within the dimensionless values of the steps of numerical integration $\tau = 0.0002$ and $h = 0.001$ for the newly formed equations, results are obtained for stepwise (up to 20% of the initial) and smooth changes in the mass flow rate at the outlet of the section. At the same time, small changes in the inlet pressure lead to large changes in the mass flow rate and flow rate, which requires a thorough study of the properties of the proposed numerical method.

V. CONCLUSION AND FUTURE WORK

A numerical method is proposed for solving a system of nonlinear equations of pipeline transport of real gas with reduction to the equations of traveling forward and backward waves. In the equation of conservation of momentum, the quadratic law of friction resistance and the path change in the height of the axis of the gas pipeline, which leads to a change in the action of the force of gravity, are taken into account, and they differ from the equations of linear and nonlinear acoustics.

The equations are solved by using an implicit scheme and taking into account the direction of propagation of the forward and backward traveling waves, where, unlike in [20], the boundary values of pressure and mass flow, as well as the slope of the path, are not constant. The nonlinear boundary condition for mass flow is reduced to a transcendental equation for velocity, which is solved by the Newton tangent method.

Due to the nonlinearity of the equations, an iterative process is organized. The results of a stationary problem with a constant gas mass flow at constant and variable slope of the route are presented, which demonstrated various options for the directional change in pressure, including pressure increase with significant negative slopes of route.

A computational experiment was carried out for the average length of a section with a given relief line and the features of the propagation of a mass flow rate of gas generated at the end of the gas pipeline section over the section were studied. It was revealed that with smooth changes in the boundary indicators, the pressure gradient, especially with large diameters of the pipeline, is formed mainly under the influence of gravity.

The method is relevant from the point of view of an adequate description of the energy intensity and reliability of the pipeline gas transportation process, as well as the pneumatic drive with various boundary conditions.

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