Automation of the control process of a gas pipeline network with a complex topological structure

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Abstract. The reliability of the gas pipeline network is determined by the perfection of the structures, the precise fullfilament of the conditions of its operation, ensuring the coordination of the flow parameters in the pipe with the parameters of the blowers. Deviation from the established mode of operation in gas pipelines can affect the stability of the system. With a significant deviation from the operating mode, various features arise, both kinematic and dynamic deviations in the flow, which leads to unstable operation of the system. Therefore, it is necessary to automate the control processes of the pipeline gas network during gas transportation, which will be based on the results of mathematical modelling of mass transfer processes in pipes to determine the main flow parameters. It is also known that the main losses and changes in flow parameters in pipelines occur along the entire length of the linear sections of the network. Therefore, to adapt these changes to specific objects, it is necessary to use more accurate mathematical models that allow to adequately control the processes in the network based on automated control systems.

1. Introduction

Based on the location of natural gas fields and the main consumers, various options for the topology of the gas pipeline network can be presented. The specific radial structure of gas pipelines is adopted to collect gas with a high concentration of condensates from wells to the reservoir [3,4]. The ring structure of gas pipelines is applicable for collecting gas from wells and for urban distribution networks. In the previous paragraph, we got acquainted with the linear structure of the gas pipeline network with branches.

This article examines a peculiar structure of the main gas pipeline network: the merger of two independent trunk lines into one two-line gas pipeline.

2. Problem Statement

The problem is posed as follows. The gas pipeline has a structure as shown in Figure 1. The gas pipeline line 1-2-3-4 at point 4 merges with the gas pipeline line 7-8-9-10-11-12-13-4 and then they form a parallel two-line section, the threads of which are interconnected by jumpers.

At points 1, 3 and 7, gas is pumped by the suppliers. At other points, gas is taken off. The lengths of the pumping and tapping bends can be neglected.

As one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations [7,11,16].

The geometrical dimensions of the sections, the rate of extraction and gas pumping are specified (except for the section and point number 6). In addition, the average value of the pressure at the point of confluence of independent lines into one (at point 4) is set. The average gas temperature is $T=293.15K$ the ratio of the densities of the transported gas and air $\Delta=0.6$. Taking into account the intensity of gas withdrawals and pumping in two single-line and double-line sections, it is necessary to restore the pressure values at the nodal points and calculate the volume of gas accumulated in the pipeline.
3. Theoretical Part

When formulating the requirements, there were no restrictions on the use of external means for displaying data and for carrying out calculations, which require significant implementation costs, if this was not directly related to the ongoing research[1,5].

The automated complex GAZOLINE has been developed, designed to solve complex problems of gas pipeline control, based on hydraulic calculations, while the selection of the necessary software modules is carried out directly in the process of solving the problem. The architecture of the automated system is shown in Figure 2.[15]

Figure 3 shows the main window of the automated control complex. In this window, the initial values of the parameters are entered and the structure of the gas supply network is shown.[15]

Figure 4 shows the window of the module for calculating and plotting graphical dependencies of the calculated parameters.

![Figure 1. Scheme of a complex gas pipeline with lumped extraction and pumping of gas.](image)

![Figure 2. Architecture of the automated system GAZOLINE.](image)
The automated gas network control complex consists of three parts: Introductory part:
– preparation of data on the gas pipeline and transported gas [15,16];
– description of simple and variable quantities;
– input of constant values, incl. diameters, equivalent roughness and lengths of elementary sections;

The second part is the GAZOLINE procedure:
Calculation of the pressure values at the nodal points and the volume of gas accumulated in the gas pipeline for a specific set of rates of gas extraction and pumping, as well as the pressure values at point 4 in Fig. 2. The third part is used to display calculations in the form of tables and graphs in Figure3, Figure4.

4. Practical Relevance

Based on the volumetric composition of the transported gas and the thermodynamic parameters of individual components, the critical temperature and pressure, molecular weight, specific heat capacity and gas constant of the transported complex gas were determined. Along with these indicators, we calculated the value \( \Delta \) – the ratio of the densities of a mixture of gas and air, which is used in hydraulic calculations [2,8,9].
The values of the critical temperature and pressure of the gas mixture were used in the procedure – functions \( z_{cp} \) to determine the value of the gas supercompressibility coefficient at the given average temperature values \( T \) and pressure \( P \) gas. For this purpose, the Redlich-Kwong equation was used, which has the third order with respect to \( z_{cp} \). So that for each complex of intensities of extraction, gas pumping and \( p_4 \) do not re-calculate the indicators of the gas pipeline and gas, their calculation was taken to the second part of the program. It consisted of stages: [6,10]

– determination of thermodynamic parameters of a given gas composition;
– determination of the parameters of the equivalent pipeline;
– calculating the values of the coefficient of consumption, the physical volume of parallel threads and sections;
– formation of signs of gas outlet and gas supply in the settlement nodes. As a result of referring to the GAZOLINE procedure, the necessary thermodynamic information about the transported gas at a temperature \( T=293.15K \).

The parameters of the section with the largest diameter were selected as an equivalent pipeline, and with their help the values of the flow coefficient were calculated (1) [12].

\[
k_{pi} = \left( \frac{D_i}{D_k} \right)^{\frac{3}{2}} \left( \frac{k_2}{k_i} \right)^{\frac{1}{2}}
\]

As can be seen from this formula, in all sections and threads of the mainline, the flow has a developed turbulent character.

The physical volume of a parallel or independent thread of an elementary section was calculated using the formula (2) [13]

\[
V_{i,j} = \pi D_{i,j}^2 l_1 / 4
\]

\( l_1 \) – length of the th elementary section.

Since the rates of extraction and pumping of gas in the data tables are presented as positive values, it was necessary to enter an array of the attribute of the withdrawal (-1) and supply (+1) of the nodal points of the scheme.

The third part of the software complex processed a complex of information \( q_i \) and \( p_4 \) for a fixed time of day and month. Depending on the number of such complexes, it was launched the required number of times.

This part of the software package consisted of the following stages:

– coordination of measurement data with the program;
– formation of expenses \( Q_i \) and calculating the ratio of expenses \( q_i \) for calculated areas [11, 17];
– calculations \( K_f \);
– restoration of pressure values at nodal points;
– calculation of the average value of pressure and the gas supercompressibility coefficient in elementary sections and threads of the gas pipeline;
– calculating the volume of accumulated gas corresponding to this complex \( q_i \) and \( p_4 \);
– preparation of information for withdrawal.

During the operation of all nodes for the supply and selection of gas, the formation of flow rates in elementary sections 1 and 7 \( q_1 \) and \( p_2 \) carried out according to the data of the simultaneous supply and extraction of gas for the site 4 (3):
Pr \, q \, Q + \, Q = 4 \, 4 \, 1 \, 3 \, 3 \, 4 \, (3)

The remaining sections (2, 3, 8, ..., 13 and 5), it was determined through the recurrence formulas (4)

\[ Q_i = Q_{i+1} + P_i \, q_i \]  \quad (4)

\( P_i \) - as already noted the sign of the selection (-1) or supply (+1) of gas in the i-th computational node.

The gas supplied from the intermediate point 3, when the gas supply from the producer 1 is stopped, is divided into lines 3-2-1 and 3-4. In this case, the gas consumption \( Q_1 \) in section 1 was determined to be equal to the selection intensity \( q_1 \) from point 1, and \( Q_2 \) in section 2 - as the sum of selections \( q_1 \) and \( q_2 \) points 1 and 2.

Then the gas flow rate in section 3 was

\[ Q_3 = q_3 \, P_3 + q_2 \, P_2 + q_1 \, P_1 \]  \quad (5)

In the rest of the sections, the costs were considered as in the variant of functioning of all gas sampling and pumping units.

As a reference flow rate, we took \( Q_x = \max_i Q_i \), where \( I \) - is a set of indices of areas \( I = \{1, 2, 3, 4, 5, 7, ..., 13\} \). The value \( Q_x \) of the coefficient of the ratio of expenses was determined using \( k_{qi} = Q_i / Q_x \), \( i \in I \) in sections and parameter of hydraulic calculation (6) [12, 14]

\[ K_f = B Q_x^2 \frac{\lambda_3}{D_3^2} \]  \quad (6)

Where \( B = 1/A^2, A = \frac{\pi T_C}{4 \, P_C} \sqrt{\frac{R}{Z T_p}} \), \( \lambda_3 = 0.11(k_3 / D_3)^{0.25} \cdot 1.1025 \)

The last factor in \( \lambda_3 \) reflects the product of the coefficient of local resistance 1.05 by 1.05 - reflecting the presence of welds in the manufacture of pipes from twisted steel sheet [17].

Parameter \( K_f \) used to restore pressure values at nodal points (7):

\[ p_{i+1} = \sqrt{p_i^2 - \varphi_i K_f \, \ell \, K_i^2 / k_{pi}^2} \]  \quad (7)

Here, the multiplier \( \varphi_i \) takes the value -1 for \( i = 1 \) and \( i = 2 \) when the supply from supplier 1 is disconnected and reflects the reverse mode of operation of sections 1 and 2.

After the pressure values are restored at the nodal points, you can begin to determine the average pressure value (8):

\[ p_{i+1} = \frac{2}{3} \left( p_i + \frac{p_{i+1}^2}{p_i + p_{i+1}} \right) \]  \quad (8)

and the values of the gas supercompressibility coefficient \( Z_i \) in the i-th section.

The average value of the pressure over the MG was generally determined as (9) [15, 17]

\[ p_{cp} = \sum_{i=1}^{n} p_{cp} \, V_i / V \]  \quad (9)

The volume of gas accumulated in MG for a given complex \( q_i \) and \( p_i \) was (10)
5. Conclusion

In order to check the stability of the solutions, the calculations of the filling of the same section of the gas pipeline were carried out under the same initial conditions and different sizes of the grid step of the method of characteristics along the coordinate Fig. 5. From the graphs shown in Fig. 5, it can be seen that when determining the parameters of the gas flow every 200 m, the solution is stable and slightly differs from the calculation results at $\Delta x = 50$ m [15].

![Figure 5](image_url)

**Figure 5.** Dependence of the results of solving the problem of filling a gas pipeline on the size of the counting cell.

For subsequent calculations, we will take the grid step of the method of characteristics along the coordinate equal to 200 m.

Fig. 6 shows the graphs of the flow pressure distribution at different points in time when filling a section of a gas pipeline with a length of $L = 20$ km, an outer diameter of $D_{tp} = 1420$ mm, and a wall thickness of $\delta = 25$ mm. Commercial gas consumption in stationary mode $Q_{KOM}$ was 160 million m$^3$. Day-1. In the initial section of the section, the pressure $p_{av} = 9.8$ MPa and temperature $T_{av} = 35$ °C are kept constant. The heat transfer coefficient from the gas flow to the environment $k$ is equal to 1 Wm$^{-2}$K$^{-1}$. The ambient temperature $T_{окр}$ is 10 °C. From the graphs presented in Figure 2, it can be seen that, according to the analytical solution, the transition process between the existing and new stationary modes is smooth. The flow pressure, gradually, without changing the tendency to increase, approaches the equilibrium value. Moreover, at each moment of time in any section of the section under consideration, it does not exceed the pressure at its beginning $p_{av} = 9.8$ MPa.
The solution shows that at the moment of closing the outlet section at the end of the gas pipeline, a pressure jump occurs (Figure 2, t = 5 s).

In the existing methods of solution, such a jump is absent due to the neglect of the action of inertial forces in the equation of motion.

Our solution also shows that the pressure growth in each of the sections of the considered section of the gas pipeline does not stop even after it reaches the equilibrium value for the new stationary regime, equal to 9.8 MPa (Figure 4, t = 45 s, although 0 to 4 km; t = 80 s, although 0 to 20 km) [9].

This is due to the presence of significant inertia in the gas flow. Part gas flowing from the end of the section to its beginning collides with another part, continuing to move in the opposite direction (accumulating capacity of the gas pipeline). Due to the deceleration of the flow, a new pressure wave arises. With its further propagation along the pipeline, the amplitude of the disturbance gradually decreases due to the dissipation of the energy of the gas flow.

The maximum value, close to 10 MPa, the pressure reaches in the final section of the filled section approximately in t = 80 s from the beginning of the unsteady process Fig. 7.

Let's compare the results of the proposed and the existing calculation method. Due to the vibrational motion of the gas available in our numerical solution, the existing solution methods tend to a new stationary regime much faster: the transient process lasts about 3000 s and 250 s, respectively.

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**Figure 6.** Gas pressure distribution along the length of the gas pipeline.
At the initial stage of filling the gas pipeline, the pressure obtained by the method of characteristics grows faster. This is due to the proliferation along the pipeline, direct and then backward waves of deceleration of the gas flow, as well as thermal effects.

Thus, this article demonstrates the features of the implementation of the generalized flow coefficient method for one- and two-line sections of a gas pipeline:

- when two threads merge;
- in a reverse mode of operation of individual sections of the gas pipeline;
- with the definition $Z$ for each section according to the volumetric composition of the transported gas and the average pressure in the section;

When determining the volume of accumulated gas with the above-mentioned features of the topology of the hydraulic network.

6. References

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