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DEVELOPMENT OF A MODEL OF THE OPTIMAL TEMPERATURE MODE OF THE MAIN GAS PIPELINE OPERATION

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The influence of the ambient air temperature on changes in the parameters and thermophysical characteristics of the gas pumped through the underground pipeline was investigated. This was done because there are no scientifically sound recommendations for the optimal gas temperature after coolers at the compressor station. The presence of the site of inversion of heat exchange between gas and soil – a change in the direction of heat exchange along the length of the gas pipeline was revealed. It was proved that the air temperature above the soil surface should be substituted into the formula for calculating the change in gas temperature along the length of the pipeline between compressor stations. This made it possible to determine quantitative changes in the thermophysical and hydraulic characteristics of the gas along the pipe length, in particular, the change in density, viscosity, heat capacity, flow regime. It is shown that the change in air temperature during the year leads to a change in the gas pressure at the end of the gas pipeline section up to 0.15 MPa. A change in air temperature by 10 °C leads to a change in gas temperature by approximately 5 °C. Analytical studies made it possible to develop practical recommendations for the power-saving operation of air coolers at compressor stations. It was determined that the optimum gas temperature at the cooler outlet will be the temperature at which the heat exchange inversion point along the length of the gas pipeline coincides with the location of the subsequent station. It is shown how to control gas cooling in air coolers. In particular, by shutting down one of several operating devices and changing the speed of the fan drive. The developed recommendations will make it possible to quickly regulate the temperature mode of the underground gas pipeline operation at optimal power consumption for the operation of the gas cooling system after gas compression

Keywords: underground gas pipeline, gas temperature, ambient air, air cooler, power consumption

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1. Introduction

Gas transportation through main pipelines is characterized by the consumption of natural gas and electricity for the needs of compressor stations. Gas is mainly used as fuel for gas turbine engines that drive blowers. Electricity is consumed for the operation of compressed gas air coolers and electric motors – blower drives. Compressing process gas consumes 100–150 times more power than its subsequent cooling. The power of the blower electric drive reaches 8 MW, and the power of the fan electric motor is up to 40 kW. Gas turbine engines are used at most compressor stations, and process gas air coolers are used at all compressor stations. When gas is compressed in blowers, its temperature rises by 20–35 °C. In the warm period of the year, the gas temperature at the blower inlet reaches 25 °C and at the blower outlet exceeds the maximum permissible gas temperature in the main pipeline 40 °C. In this case, gas cooling is required.

Main gas pipelines are laid underground, above ground in embankments, above ground, under water. The length of the underground laying is predominant in the temperate climatic zone. Gas enters the pipeline after the compressor station at a temperature of 40 °C and below. When laying underground, the soil temperature at the pipeline depth is significantly lower. In the natural state, the soil temperature is (10÷16) °C. When gas moves over distances of 100÷150 km to the next compressor station, its temperature decreases [1].

The relevance of research on this topic is due to the fact that there are no scientifically sound recommendations for the optimal temperature of natural gas at the outlet of air coolers at a compressor station.

The ideal limit for natural gas cooling in air coolers is ambient temperature. The operating instructions for the compressor station are standardized to maintain the gas temperature after cooling within the specified limits [2]. These limits are set by the dispatching service, taking into account the maintenance of the optimal mode of gas transportation. What is meant by the optimal mode is not specified. Additional criteria are:

- ensuring long-term reliability of the main gas pipeline;
- preservation of anti-corrosion insulation;
- hydrate prevention;
- ambient temperature.

The known physical model of heat exchange of an underground gas pipeline with the environment requires correction to determine the optimal gas temperature at the outlet of air coolers.

2. Literature review data and problem statement

The flow temperature in the main pipeline is higher than the temperature of the surrounding soil. The work [3] presents the results of calculations of temperature fields in different soils around the Keystone transcontinental oil pipeline for different climatic conditions. Based on the analysis of the presented graphical data, two conclusions can be drawn:

– the temperature of the soil around the pipeline differs significantly from the temperature of the natural soil at the same depth;

– the heat of the flow from the pipeline is ultimately transferred to the air above the ground surface.

The issue of the change in the pipe flow temperature with a change in the air temperature remains unresolved.

In [4], the profiles of the temperature field around a pipeline with a heated liquid during its shutdown, downtime and restart are considered. The influence of the ambient air temperature on the temperature field is noted. The issue of how the gas flow temperature changes when the air temperature changes remains unresolved.

There are various methods for calculating the temperature change of the heated flow in pipelines. The paper [5] considers a method for calculating the temperature field in the soil around a pipeline with a hot medium without taking into account the Joule-Thomson effect and the outside air temperature. In [6], it is proposed to take into account the change in the temperature of the gas flow in the underwater pipeline depending on the height of the gas column at a constant temperature of sea water. The question of the influence of water temperature on gas flow characteristics remains unresolved. Also in [6], it is proposed to design underground gas pipelines in complex non-isothermal conditions with an assumption that neglects the influence of the ambient air temperature and soil state on the change of the transported gas temperature. In this case, the Joule-Thomson effect is taken into account. The reason for this is the difficulty associated with complex calculations of the effect of air temperature on the gas flow characteristics. In [7], a technique is given in which the driving force of heat transfer is the difference between the gas temperature and the surrounding soil temperature. The soil temperature is taken and remains unchanged during the year-round operation. The issue of the influence of air temperature changes on the driving force of heat transfer remains unresolved. The work [8] simulates the change in the temperature of the hydrogen-methane mixture in the main pipeline at a constant ambient temperature. The issue of the influence of the air temperature on the pipeline flow temperature remains unresolved. In [9], the authors note that in underground gas pipelines in the fields, the gas temperature at the end of the section was recorded below the temperature of the soil in its natural state. The experimental result differs from the data of calculations using known methods. The reason for this is the incorrect model. In [10], the authors analyze the change in the Joule-Thomson coefficient for methane with a change in its pressure and temperature. A possible inversion of the change in heat transfer for typical gas pumping conditions is shown. The paper also analyzes the effect of pressure and temperature changes on the thermophysical properties of a methane-hydrogen mixture in the main pipeline. The calculation of the change in gas temperature along the length of the pipeline was carried out according to the formula in which the soil temperature was taken as the ambient temperature. The calculated change in density, specific heat, Joule-Thomson coefficient along the length of various-diameter gas pipelines is shown. The issue of the air temperature influence on the gas flow characteristics remained unresolved. In [11], the change in the temperature of the gas pipeline wall along its length is investigated taking into account the Joule-Thomson effect, but without the change in the temperature of the environment – air.

All this testifies to the feasibility of studying the effect of air temperature on the cooling of the gas flow in an underground pipeline. Such studies can provide recommendations for the optimal operation of the cooling system at the compressor station.

3. The aim and objectives of the study

The aim of the study is to substantiate the optimal value of the temperature of the cooled natural gas at the compressor station. This will make it possible to optimize the current operating power inputs.

To achieve the aim, the following objectives were set:

– to propose a physical model of natural gas cooling in an underground main pipeline, which will take into account the current change in the ambient temperature – outdoor air;

– to perform calculations of changes in the temperature, pressure, hydraulic characteristics and thermophysical properties of the gas flow along the length of the main pipeline in accordance with the proposed physical model;

– to analyze the simulation results and substantiate the optimal operating mode of the natural gas cooling system at the compressor station.

4. Research materials and methods

The solution to the assigned tasks is based on an analytical approach. It is believed that the parameters of gas movement do not change over time, so the mathematical model is stationary. Since the thermal interaction of the pipeline with the environment is taken into account, its non-isothermality was adopted when developing a mathematical model. Gas parameters and properties change only along the length of the pipeline. That is, the gas motion model is one-dimensional. Due to the low density of gas, it is assumed that the influence of the Coriolis and gravitational forces is insignificant.

Testing of this model was carried out during a computational experiment on the basis of a section of the main gas pipeline with randomly selected input data. To construct dependences of gas temperature and pressure on its coordinate, the methods of rational experimental design theory were used.

To carry out a numerical experiment, software has been developed that implements the proposed mathematical model of gas movement. When writing the program, an object-oriented approach based on the Python programming language was used. The Matplotlib library was used to visualize the data.

The hardware was a computer with a dual-core processor and 8 GB RAM. The processor speed is 2.5 GHz.

Calculation of the thermophysical properties of the gas was carried out on the basis of average pressure and temperature values in the gas pipeline section. Since the final gas pressure and temperature were considered unknown, an iterative approach was used to calculate the average temperature. To achieve the accuracy required for practical purposes, the gas pipeline under consideration was divided into equal sections of 1,000 m, which is 0.67 % of the total length. Calculations were carried out sequentially at each site.

5. Results of the study of the temperature mode of operation of the main gas pipeline section

5. 1. Investigation of the physical model of natural gas cooling taking into account the ambient temperature

The method for calculating the change in the temperature of a stationary real gas flow is based on a system of differential equations.

The equation of flow continuity:

$$Q = \rho W_g S = \text{const}. \qquad (1)$$

The equation of flow hydrodynamics:

$$\rho W_g \left[\frac{dW_g}{dx} + \frac{dP}{dx}\right] = -\lambda \frac{1}{d_i} \cdot \frac{\rho W_g^{\,2}}{2} - \rho g \frac{dz}{dx}. \qquad (2)$$

The equation of the thermal state of gas during its heat exchange with the medium:

$$\frac{d}{dx}\left[\frac{a_k W_g^{\,2}}{2} + H(P,T)\right] = -\frac{\pi d_i K_{med}(T - T_{env})}{Q_m} - g\frac{dz}{dx}. \qquad (3)$$

The equation of gas state:

$$P = Z(P,T) \cdot \rho \cdot R \cdot T, \qquad (4)$$

where Q_m – gas mass flow rate, kg/s; $\rho(x)$ – current gas density, kg/m^3; $P(x)$ and $T(x)$ – current gas pressure (Pa) and temperature (K), respectively; W_g – gas flow rate, m/s; S – pipeline flow area, m^2; d_i – pipeline diameter, m; λ – coefficient of hydraulic resistance; g – acceleration of gravity, m/s^2; $z(x)$ – vertical coordinate of the position of the pipe section axis, m; x – coordinate of the pipe section along the length of the gas pipeline, m; α_k – Coriolis coefficient; H – specific enthalpy of gas state, kJ/kg; K_{med} – average coefficient of heat transfer from the gas flow to the environment, W/(m^2·K); T_{env} – ambient temperature, K; Z – natural gas compressibility factor; R – gas constant for natural gas, J/(kg·K).

The left side of equation (2) represents the change in the total pressure of the flow in an elementary section along the pipe length. The right-hand side of equation (2) represents the loss of the total flow pressure on the elementary pipe section dx to overcome the hydraulic resistance and to take into account the pipeline profile.

The left side of equation (3) represents the change in the specific heat power of the flow in the elementary section dx. The right-hand side of this equation characterizes the heat exchange between the gas pipeline and the environment in the dx section.

Consider gas transport at the initial stationary parameters of the environment and gas. For a simpler and more convenient calculation of the characteristics of a stationary process, the system of differential equations is replaced with algebraic expressions. This technique is used in regulatory methods for gas pipeline design [6].

The change in gas temperature in the pipeline is due to its heat exchange with the environment and the Joule-Thomson effect. The more the gas in the pipeline cools down or the lower its temperature (T_{fin}) at the inlet to the blower of the next compressor station, the less power consumption for gas compression will be. In the polytropic compression process, the specific polytropic work (H_p) of the compressor is calculated by the formula in kJ/kg:

$$H_p = Z_{fin} \cdot R \cdot T_{fin} \cdot \frac{(\varepsilon^m - 1)}{m}, \qquad (5)$$

where Z_{fin} – gas compressibility coefficient at inlet pressure and temperature; ε – gas compression ratio; $m=(n-1)/n$ – volumetric indicator of the polytropic process; n – polytropic exponent.

On the other hand, a lower temperature of fuel gas in a pumping unit with a gas turbine drive leads to increased consumption, which is undesirable. In this case, the fuel gas must be heated to a flash point from a rather low temperature.

A decrease in the blower inlet natural gas temperature (T_{fin}) leads to a decrease in its outlet temperature (T_k). The increase in gas temperature during compression in the blower is calculated:

$$T_k = T_{fin} \cdot \varepsilon^{\frac{m}{\eta}}, \qquad (6)$$

where η – efficiency in the polytropic process of gas compression, fraction.

When designing main gas pipelines, it is recommended to take an increase in gas temperature during the compression process by (30÷35) °C.

Lowering the gas temperature after compression leads to a decrease in the heat load on air coolers.

The temperature of the cooled gas is regulated at the compressor station by the number of operating air coolers – by turning them on or off. If this is not possible, the operating mode of the compressor station is changed.

Naturally, the gas temperature at the end of the main pipeline section depends on the temperature at the beginning of the section. The current gas temperature in any section of the pipeline along the length of its section is determined by the formula that is valid for calculating the final gas temperature at the end of the section. In this case, the section length «L» is substituted with the current length «x» in the formula [1]:

$$\begin{aligned} T_{fin} &= T_{env} + (T_{init} - T_{env}) \cdot e^{-a \cdot L} - \\ &- D_i \cdot \frac{P_{init}^2 - P_{fin}^2}{2 \cdot a \cdot L \cdot P_{med}} \cdot \left(1 - e^{-a \cdot L}\right), \end{aligned} \qquad (7)$$

P_{init} – gas pressure at $x=0$, MPa; P_{fin} – gas pressure at $x=L$, MPa; P_{med} – average gas pressure in the section L, MPa; D_i – average value of the Joule-Thomson coefficient for natural gas of a given composition in the pipeline section at P_{med} and T_{med}, K/MPa.

Table 1 shows approximate values of the Joule-Thomson coefficients, calculated according to the recommendations [6]. From Table 1, it follows that the values of the coefficients decrease with increasing pressure and temperature.

a – coefficient (1/km), which is determined:

$$a = 0.0864 \cdot \frac{K_{med} \cdot d_o}{Q \cdot \rho_{st} \cdot C_P}, \qquad (8)$$

T_{env} – calculated ambient temperature, K; T_{init} – gas temperature at the beginning of the gas pipeline section at $x=0$, K;

d_o – outer diameter of the gas pipeline, m; K_{med} – average coefficient of heat transfer from gas to the environment in the pipeline section, W/(m^2·K); C_p – average isobaric heat capacity of gas, kJ/(kg·K). With decreasing gas temperature and constant pressure, C_p increases. With a decrease in gas pressure and constant temperature, C_p decreases. With a simultaneous decrease in gas temperature and pressure in the pipeline, C_p decreases. The decrease in the C_p value in the gas pipeline does not exceed 8 %; Q – gas pipeline capacity, million m^3/day; ρ_{st} – density of natural gas at 293 K and 0.1013 MPa, kg/m^3; L – length of the gas pipeline section, km; 0.0864 – dimensionality matching coefficient.

When designing gas pipelines, as a result of hydraulic calculations, the loss of gas pressure between adjacent compressor stations is approximately known. In other words, the P_{init} and P_{fin} values are known. Intermediate gas pressure P_x can be calculated:

$$P_x = \sqrt{P_{init}^2 - \left(P_{init}^2 - P_{fin}^2\right)\cdot\frac{x}{L}}. \qquad (9)$$

Calculation of the average heat transfer value K_{med}, W/(m^2·K) is carried out depending on the method of gas pipeline laying. When laying underground:

$$\frac{1}{K_{med}} = \sum R + \frac{1}{\alpha_2}, \qquad (10)$$

where $\sum R$ – sum of thermal resistances (Fig. 1), m^2·K/W,

$$\sum R = R_g + R_w + R_{is}, \qquad (11)$$

R_g – resistance of heat transfer from the gas flow to the pipe wall, m^2·K/W; R_w – thermal resistance of the pipe wall, m^2·K/W; R_{is} – thermal resistance of the insulation layer on the pipe, m^2·K/W.

Table 1

Approximate values of the Joule Thomson coefficients for natural gas of the Shebelinka field, K/MPa

Pressure (P_{med}), MPa	Temperature (T_{med}), K					
	270	280	290	300	310	320
1	5.39	5.13	4.60	4.53	4.31	4.05
2	5.38	5.06	4.62	4.44	4.17	3.91
3	5.36	4.98	4.64	4.32	4.04	3.75
4	5.30	4.90	4.57	4.24	3.98	3.70
5	5.18	4.82	4.47	4.15	3.89	3.64
6	5.02	4.64	4.33	4.01	3.76	3.52
7	4.83	4.43	4.14	3.84	3.60	3.38

For underground gas pipelines, the conditional heat transfer coefficient (α_2) is calculated using the Forchheimer-Greber formula, W/(m^2·K):

$$\alpha_2 = \frac{2\cdot\lambda_{soil}}{d_o}\cdot\ln\left[\frac{2h_0}{d_o} + \sqrt{\left(\frac{2h_0}{d_o}\right)^2 - 1}\right], \qquad (12)$$

where λ_{soil} – average coefficient of thermal conductivity of the soil, depending on its composition, temperature and humidity, W/(m·K); h_0 – pipe axis depth, m.

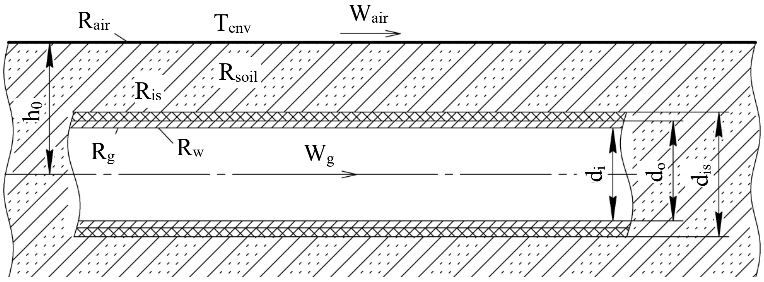

Fig. 1. To the process of heat exchange of gas with the environment

According to the designations in Fig. 1, coefficient (α_2) is the reciprocal of the sum of the thermal resistance of the soil (R_{soil}) and the resistance of heat transfer from the soil surface to the air (R_{air}).

The depth to the top of the pipe (h) for underground laying is 0.8 m for a diameter of less than 1,000 mm and 1 m for large diameters. For pipes with a diameter of more than 300 mm, the ratio $(h_0/d_o)<3$ is valid. In this case, the thermal resistance at the «soil surface – air» boundary should be taken into account. This resistance is replaced with the thermal resistance of the soil of fictitious thickness ($h_{F.soil}$). The thermal resistance of the snow cover, if any, (h_{sn}) is taken into account in a similar way. The value h_{0F} should be substituted into formula (12) instead of the value h_0:

$$h_{0F} = h_0 + h_{F.soil} + h_{sn}. \qquad (13)$$

The choice of the calculated ambient temperature T_{env} is made depending on the method of gas pipeline laying. In the existing methods for underground laying, the T_{env} value is taken equal to the average soil temperature value T_{soil} for the period under consideration at the depth of the pipeline axis in the natural thermal state.

5. 2. Investigation of changes in the thermophysical properties of gas and parameters of its movement in the pipeline

Fig. 2 shows an example of a gas pressure change along the length of the gas pipeline. The dependency has a bulge upward. The pressure loss of the pipe flow is influenced by the mode of movement, the temperature and condition of the soil, the temperature and speed of wind above the soil surface have almost no effect.

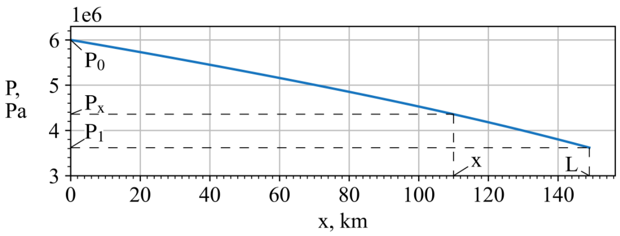

Fig. 2. Change in gas pressure along the length of the main pipeline

Fig. 3, 4 show graphically the change in gas characteristics obtained by computational modeling. The need to predict the final gas temperature (Fig. 3) and pressure (Fig. 4) is due to the fact that they affect the operating mode of the next compressor station along the length.

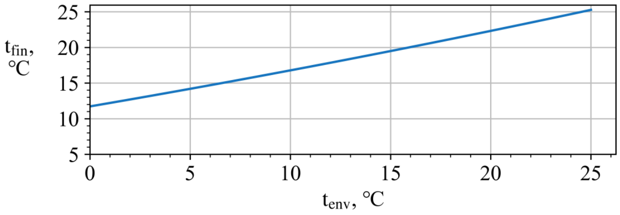

Fig. 3. Dependence of the temperature change of the transported gas at the end of the gas pipeline section on the ambient temperature

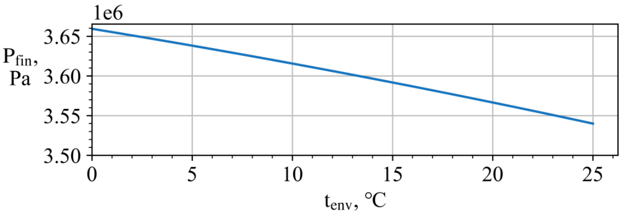

Fig. 4. Dependence of the pressure change of the transported gas at the end of the gas pipeline section on the ambient temperature

Due to the equation of state (4), during the numerical experiment, the dependence of the density ρ on the coordinate x was obtained (Fig. 5).

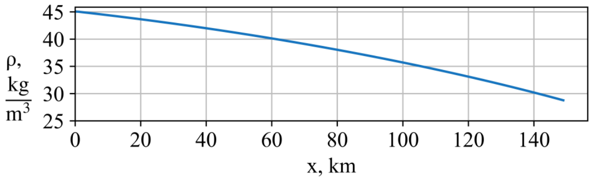

Fig. 5. Dependence of the current density of the transported gas along the length of the pipeline section

Fig. 6 shows a graph of the change in the coefficient of kinematic viscosity along the length of the pipeline. Viscosity affects the gas flow behavior. It is generally accepted that the gas movement mode in the main gas pipelines is turbulent in the area of quadratic friction.

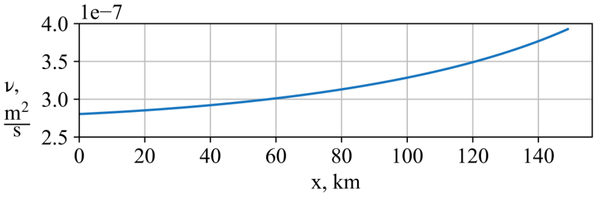

Fig. 6. Dependence of the change in the current coefficient of kinematic viscosity of gas along the length of the pipeline section

Fig. 7 shows the change in the dynamic viscosity of gas along the length of the pipeline. From the position of the curve in Fig. 7, it follows that the change in the dynamic viscosity is more affected by the change in the gas density than the change in the kinematic viscosity coefficient.

$$\mu = \nu \cdot \rho. \tag{14}$$

The graph in Fig. 8 shows a slight change in the specific heat of the gas.

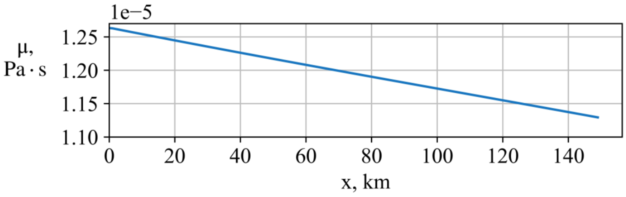

Fig. 7. Dependence of the change in the current coefficient of dynamic gas viscosity along the length of the pipeline section

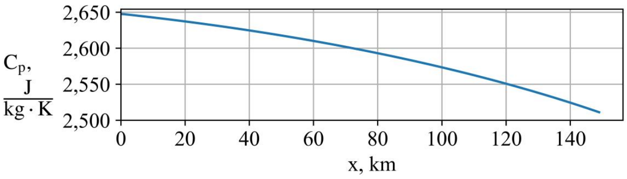

Fig. 8. Dependence of the current specific heat capacity of gas along the length of the pipeline section

The decrease in heat capacity compared to the value at the beginning of the pipeline is 5.7 %.

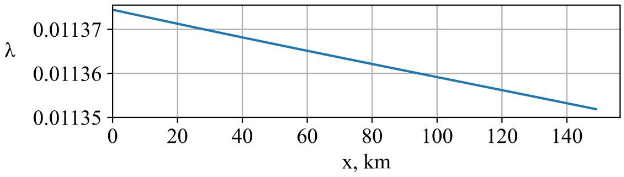

Fig. 9. Change in the coefficient of hydraulic resistance along the length of the gas pipeline section

The temperature and pressure of natural gas at the end of the pipeline section according to formulas (7) and (8) depend not only on the ambient temperature T_{env}, but also on the heat transfer coefficient K_{med}.

During the operation of the gas pipeline, the K_{med} value changes depending on soil moisture. Soil moisture is the ratio of the mass of water in the soil pores (free water) to the mass of dry soil dried at 105 °C. Soil moisture is expressed as a percentage.

A change in soil moisture leads to a change in the thermal conductivity of the soil (Fig. 10), respectively, to a change in the heat transfer coefficient and heat exchange of the transported gas with the environment.

Changes in gas temperature and pressure with increasing soil moisture lead to a decrease in the gas velocity, as shown in Fig. 13.

The graph in Fig. 14 shows the dependence of the average kinematic viscosity along the length of the gas pipeline on the moisture content of the surrounding soil.

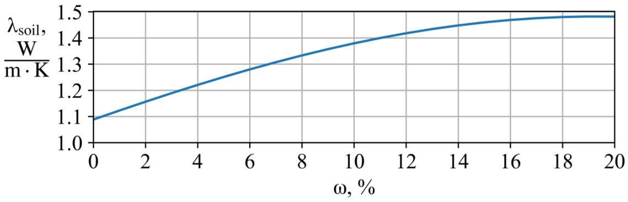

Fig. 10. Dependence of the coefficient of thermal conductivity of loamy soil on its moisture content

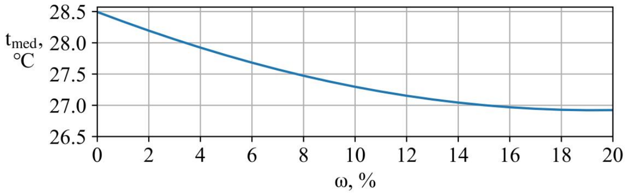

Fig. 11. Dependence of the temperature change of the transported gas at the end of the pipeline section on the moisture change of soil around the gas pipeline

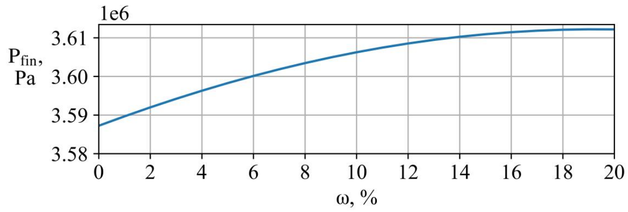

Fig. 12. Dependence of the change in the pressure of the transported gas at the end of the pipeline section on the moisture change of soil around the gas pipeline

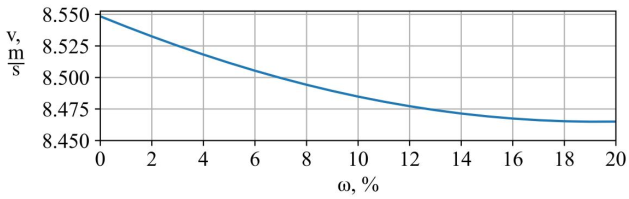

Fig. 13. Dependence of the change in the gas velocity in the pipeline with a change in the moisture content of the surrounding soil

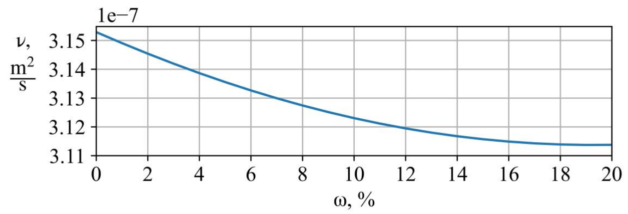

Fig. 14. Dependence of the change in the coefficient of kinematic viscosity of the gas in the pipeline with a change in the moisture content of the surrounding soil

A change in gas pressure and temperature with increasing soil moisture leads to a decrease in the kinematic viscosity of the gas by 1.5 %, which is a positive effect (Fig. 14).

5. 3. Results of modeling analysis and substantiation of the optimal temperature mode for the operation of the natural gas cooling system at the compressor station

Computational modeling of the gas temperature change depending on the outside air temperature is performed for a stationary mode (7). T_{env} (7) is the ambient temperature.

Heat transfer from the gas to the environment occurs due to the temperature difference between the gas and the environment. When laying a gas pipeline underground, the ambient temperature previously, in known sources, was taken to be the natural temperature of the soil assuming that it is the same along the length of the pipeline. The temperature difference decreases along the length of the gas pipeline due to heat exchange and due to the Joule-Thomson effect.

The lower the gas temperature and the higher its pressure at the inlet to the compressor station, the lower the power consumption for gas compression and its subsequent cooling in air coolers.

Fig. 15 shows examples of changes in the temperature of the transported gas at different values of air temperature above the soil surface. Curve 1 in Fig. 15 is calculated at an ambient temperature of 25 °C. Curve 2 is plotted at an air temperature equal to the natural temperature of the soil at the depth of the pipe.

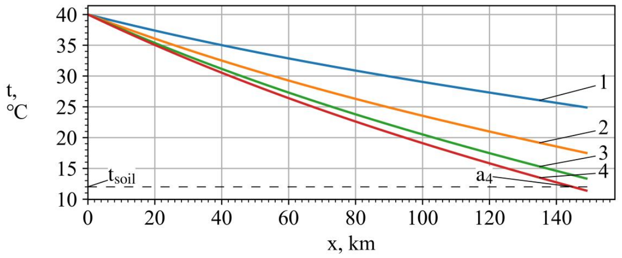

Fig. 15. Change in gas temperature along the length of the main gas pipeline at the initial gas temperature — t_{init}=40 °C, soil temperature — t_{soil}=12 °C and air temperature t_{env}: 1 — 25 °C; 2 — 12 °C; 3 — 4 °C; 4 — 0 °C

Point «a_4» is characterized by the same value of the current gas temperature and soil temperature.

The calculation results for the influence of the AC (air cooler) operation on the temperature change of the transported gas are shown in Fig. 16.

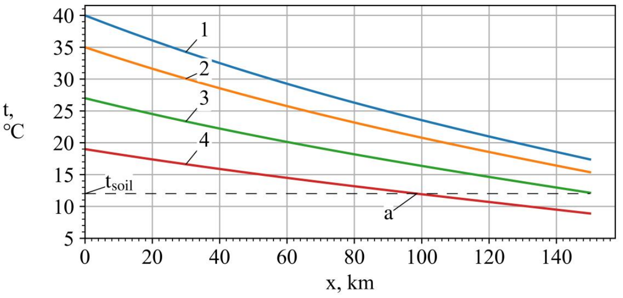

Fig. 16. Change in gas temperature along the length of the pipeline at t_{env}=t_{soil}: 1 — gas cooling by AC to t_{init}=40 °C; 2 — gas cooling by AC to t_{init}=35 °C; 3 — gas cooling by AC to t_{init}=27 °C; 4 — gas cooling by AC to t_{init}= 19 °C; a — heat exchange inversion site (t_g=t_{soil})

The position of curve 2 in Fig. 16 illustrates that at the end of the pipeline section, the gas temperature will be 6 °C higher than the ground temperature. There is no heat transfer inversion point on the gas pipeline.

6. Discussion of the results of mathematical modeling of the gas pipeline section

A change in air temperature above the ground surface affects the temperature and pressure of the gas that is transported through the underground pipeline. A change in the current values of temperature and pressure of natural gas along the length of the pipe leads to a change in its current thermophysical properties and a change in the coefficient of hydraulic resistance.

Knowledge of thermophysical properties allows modeling the current change in the coefficient of hydraulic resistance along the length of the pipeline section.

The roughness of the pipe inner surface and the presence of contamination do not depend on the air temperature above the ground surface. As follows from the calculation results (Fig. 9), the change in the hydraulic resistance coefficient along the length of the pipeline due to the change in air temperature is caused by the change in the density and viscosity of the gas along the length. The decrease in the gas density due to the pressure drop is accompanied by an increase in the gas velocity. An increase in the coefficient of kinematic viscosity of the gas along the length of the pipeline also contributes to a change in the Reynolds number, with which the coefficient of hydraulic resistance is calculated. As follows from Fig. 9, the decrease in the coefficient of hydraulic resistance along the length of the pipeline is almost insignificant – up to 0.02 %.

A series of calculations performed according to the selected mathematical model made it possible to determine a number of regularities of the influence of soil moisture on the parameters of gas transportation. The calculations show that soil moisture practically does not affect the gas velocity and the coefficient of hydraulic resistance of the pipeline (decrease by 0.0044 %).

With an increase in soil moisture from 0 to 20 %, the following regularities were also recorded:

– the coefficient of thermal conductivity of the soil increases by 31 %;

– the gas temperature at the end of the section is further reduced by 2 °C (Fig. 11);

– the gas pressure at the end of the gas pipeline section increases by 20 kPa (Fig. 12).

As can be seen from Fig. 10, 11, an increase in soil moisture improves heat exchange of gas with the environment. Higher humidity corresponds to higher gas pressure and temperature at the end of the gas pipeline section and a higher value of the soil thermal conductivity coefficient, which is a positive effect.

In gas transportation systems, five blowers (on average) operate simultaneously for one main gas pipeline. In gas cooling systems at the compressor station, each blower is equipped with one AC. If necessary, one of several operating AC can be turned off. It also follows that in order to save power resources, the speed of the electric motor in the AC fan drive should be regulated depending on the value of the gas temperature at the end of the gas pipeline section at the inlet to the next compressor station.

Another solution is modular design of the gas cooling system at the compressor station. In this case, there are several AC per blower. Regulation of the gas temperature at the outlet of the compressor station is achieved by switching on or off individual AC.

The work [12] notes the promising use of variable-speed fans at compressor stations. This makes it possible to adapt gas coolers to different seasonal and operating conditions. The cooling effect not only changes with the respective average monthly outdoor temperature, but also with changes in the daily or hourly operation of the station. Analysis of the power consumption of the gas cooling system shows that annual power savings, taking into account the current changes in the daytime temperature of the outside air, can reach 25 % compared to regulating the operation of air coolers by the average monthly temperature. The paper notes that the increase in the efficiency of gas cooling technologies goes in two directions: the use of small-sized air coolers in the required quantity and variable-speed fan drives.

Therefore, there is reason to believe that when designing and operating main gas pipelines, the dependence of the gas pipeline operating mode on the current climatic conditions is not sufficiently taken into account [13]. Regularities of the influence of the ambient temperature on the gas pipeline temperature mode can be revealed by the software [14].

Analysis of the results of calculating the change in gas temperature along the length of the main gas pipeline with air temperature variation and an initial gas temperature of 40 °C (Fig. 15) shows the following. At an air temperature of 12 °C (curve 2), the gas temperature at the end of the gas pipeline section turns out to be 6 °C higher than the ground temperature. It follows that gas cooling in air coolers (AC) to 40 °C after compression at the previous compressor station in this case is not optimal. It is necessary to cool the gas to a lower temperature so that at the end of the pipeline section the gas temperature becomes equal to the ground temperature. In other words, you need to spend additional power resources for the AC operation.

Curve 4 in Fig. 15 shows that at a rather low air temperature, the gas is cooled at the end of the section to a temperature several degrees below the temperature of the soil in its natural state. This is due to the Joule-Thomson effect. In this case, it is recommended to reduce the effect of gas cooling in the AC by reducing the power consumption for the AC fan drive.

Curve 3 in Fig. 16 corresponds to gas cooling in AC to 27 °C. At this temperature, the calculated gas temperature at the end of the section will be equal to the soil temperature of 12 °C and the adopted T_{env}=285 K.

With a further decrease in the temperature of the compressed gas in the AC, the location of point «*a*» on curve 3 will correspond to the current section of the pipeline section. The mode of gas cooling in the AC, in which the gas temperature in the current pipeline section is equal to the ground temperature, will not be optimal.

From the location of curve 3 in Fig. 16, it can be seen that in the warm season (t_{env}>12 °C), it is recommended to cool gas in the AC to 27 °C. Cooling to a temperature of 19 °C (curve 3) is impractical, since the heat exchange inversion point is located at 2/3 of the section length. The power of the AC fans will be partially spent on cooling the soil for 1/3 of the section length.

The research results are valid for a gas pipeline laid in the ground without possible heat sources and sinks. The model does not take into account possible soil freezing with a water–ice phase transition at negative air temperatures. For the further development of the study, it seems important for practice to study the inertia of the gas temperature change in relation to the air temperature change.

7. Conclusions

1. The proposed physical model for cooling the transported gas in an underground pipeline assumes the transfer of heat from the gas to air above the soil surface. In the model, the driving force of heat transfer is the difference between the initial gas temperature and the air temperature. During the year, the driving force of heat transfer varies from 5 °C to 60 °C. The calculated gas temperature in the pipeline section changes accordingly. The known physical model does

not take into account the possible change in air temperature. In this case, the temperature difference is determined between the gas temperature and the soil temperature, which is assumed to be constant. The driving force of heat transfer does not change and is approximately 25 °C.

2. Modeling the change in gas temperature along the length of the underground main pipeline allows determining the section in which the gas temperature becomes equal to the ground temperature. This section is the point of heat transfer inversion. With the further flow movement, the gas temperature will be lower than the ground temperature due to the Joule-Thomson effect. The gas will be heated by the ground. When calculating by the known model, there is no inversion point.

Changes in air temperature throughout the year lead to a change in gas pressure at the end of the gas pipeline section. The gas pressure change is up to 150 kPa.

A change in air temperature by 10 °C leads to a change in the gas temperature at the end of the section by approximately 5 °C.

The results of modeling the current values of the thermophysical properties of gas along the length of the pipeline section showed for the end point:

– reduction of density by 50 %;
– increase in the coefficient of kinematic viscosity by 30 %;
– decrease in the coefficient of dynamic viscosity by 13 %;
– decrease in specific heat by 6 %.

The change in the thermophysical properties of the gas led to a decrease in the coefficient of hydraulic resistance of the pipeline at the end of the section by 0.2 %.

The results of the study of an increase in soil moisture up to 20 % on the gas transportation characteristics showed:

– increase in the coefficient of thermal conductivity of loamy soil by 36 %;
– increase in gas pressure at the end of the section by 25 kPa;
– decrease in gas temperature at the end of the section by 1.5 °C;
– reduction of gas velocity at the end of the section by 1 %;
– decrease in the coefficient of kinematic viscosity of the gas by 1.5 %.

3. The coordinate of the heat exchange inversion point along the pipe length depends on the gas temperature at the pipe inlet and the air temperature.

The optimal temperature mode for gas transportation is the location of the inversion point at the inlet to the next compressor station.

If the gas temperature at the pipeline inlet is 40 °C, and the gas temperature at the end of the pipeline section is higher than the temperature of the soil in its natural state, the gas temperature at the pipeline inlet should be lowered.

If the gas temperature at the pipeline inlet is below 40 °C, and the gas temperature at the end of the pipeline section is below the temperature of the soil in its natural state, the gas temperature at the pipeline inlet should be increased.

If at a low air temperature and a gas inlet temperature of 40 °C at the end of the section, the gas temperature is lower than the ground temperature, there is no need to adjust the temperature.

A change in the gas temperature at the pipeline inlet is carried out by changing the power consumption of air coolers.

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