UDC 658.012.011.56:658.512, 662.987
DOI: 10.15587/1729-4061.2018.121667

THEORETICAL AND APPLIED ASPECTS OF USING A THERMAL PUMP EFFECT IN GAS PIPELINE SYSTEMS

На основі класичного методу розрахунку параметрів газопровідних мереж з використанням електрогідравлічної аналогії розроблена математична модель об'єкту – процесу транспортування газу в промисловому трубопроводі. Предмет дослідження – зміна температури після проходження газом міжниккового дроселюючого пристрою, що викликає ефект теплового насосу в приймаючій нитці газопроводу. Запропоновано використати трасовогазодинамічні теплові насоси для мінімізації ризику корко- та гідратоутворення в УМГ «Харківстрансгаз»

Ключові слова: газотранспортна система, міжниткова перемичка, дросель-ефект, трасовий тепловий насос, електрогідравлічна аналогія

На основе классического метода расчета параметров газопроводных сетей с использованием электрогидравлической аналогии разработана математическая модель объекта – процесса транспортировки газа в промышленном трубопроводе. Предмет исследования – изменение температуры после прохождения газом междуниточного дросселирующего устройства, которое вызывает эффект теплового насоса в принимающей нитке газопровода. Предложено использовать трассовые-газодинамические тепловые насосы для минимизации риска корко- и гидратообразования в УМГ «Харкивстрансгаз»

Ключевые слова: газотранспортная система, междуниточная перемычка, дроссель-эффект, трассовый тепловой насос, электрогидравлическая аналогия

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1. Introduction

When transporting natural gas, hydrate and gas-dynamic plugs are formed in the gas pipeline because of low temperature and non-stationary processes in certain places. This reduces throughput and reliability of the gas supply network in general. For local heating of the gas stream to prevent sedimentation, inlet and longitudinal heaters, thermal insulation of the preceding upstream section, intermediate or edge thermal insulation of the target section, remote beam or electromagnetic radiation are used. In recent years, heaters are used in combination with thermal pumps which reduces energy costs of heating-up.

In regime-running, scheduled, repair and emergency switch-overs of separate sections of gas pipelines, branches of distribution pipelines or parts of transit mains, non-stationary modes of operation of throttling devices at the gas-transport system (GTS) sections take place [1–3]. Change of longitudinal temperatures in the pipelines determines the effect of thermal pumps [4–6] the use of which is potentially more economical than that of heaters with external energy supply for heating.

The study of the use of the thermal pump effect for local heating of the dangerous hydrate-accumulating sections of gas pipelines is urgent today. These are loops, manifolds, bridges and branches of multi-strand gas pipelines. Redistribution of flow speeds in the network thru redistribution of pressures with the use of throttling on bridges and closure devices makes it possible to change the temperature map of the network, specifically, reduce temperature to the level lower than the ambient temperature. Presence of low-potential heat in the adjacent environment determines the possibility of its useful utilization. Pressure differential in the throttling section causes redistribution of thermal energy from the external media to the transported medium (gas). As a result, regions of local heating (cooling) appear which is used for prevention of hydrate accumulation and elimination of gas-dynamic plugs. Consequently, a line hydro-gas-dynamic thermal pump is a device with distributed parameters that transfers low-potential thermal energy from environment to the target pipeline loop. This pump contains a throttling element which causes local heating of the transported product in one zone and cooling in the other and does not contain special secondary heat-transfer loops. The role of the secondary loops is performed by separate sections of the pipeline.

In a multi-strand pipeline, the method of simulating predictive feed-forward control of technological processes is used to solve the problem. To predict the effect of throttling in the elements of complex gas transmission nets, it is necessary to develop a mathematical model of the gas-dynamic thermal pump integrated in the network diagram.

2. Literature review and problem statement

A comparative analysis of stationary and non-stationary models of heat exchange between a gas pipeline network and the environment was performed in paper [8]. The degree of influence of ground body on the temperature dynamics in pipelines is estimated by the classical equations of heat transfer and longitudinal heat exchange. It was proved that the non-stationary model of heat exchange which is recommended by the author to use in calculation of high-pressure gas pipeline networks is the more precise.

The effect of boundary temperature conditions on the heat exchange between the ground body and the underground pipeline is considered in [9]. One and two-dimensional models were used to calculate thermal conductivity. It is asserted that accuracy of ground temperature prediction worsens when air temperature is used in estimation of boundary condition of the ground surface. In order to more accurately predict the heat exchange efficiency, it is proposed to take into account the effect of heat accumulation as well as the actual temperature of gas in the pipeline.

Heat exchange between a mixture of air and water and the environment was investigated in work [10]. Two-phase state of flow, its type (laminar or turbulent) and turbulence intensity are taken into account. It has been established that the heat exchange efficiency varies almost twice as the angle of inclination of the pipes changes and up to 5 times when geometry of flows of individual phase components is changed. Phase transformations assume the process of hydrate formation which causes dynamic change of the flow geometry.

Work [11] offers a new approach to calculating the Joule-Thomson coefficient of natural gas, which is close by its precision to the standard branch procedure of ISO/TR 9464. A raise of accuracy was achieved, specifically by taking into account local throttling as components of a cumulative throttle effect.

In [12], throttling is modeled when passing a narrowing device, a diaphragm. Comparison is made with the branch document, ISO-5167 and a polynomial surrogate based on the GMDH algorithm is proposed. The result of determination of the throttle effect is correct but it is cumbersome for calculation of multi-strand pipelines. Therefore, it is expedient to develop an empirical dependence of consideration of the Joule-Thomson effect which will shorten the time of preparation of initial data and improve calculation accuracy.

Kashcheev-Friesabad model is proposed in [13] to describe the hydration process. The speed of growth of hydrate formation in gas pipelines without and with addition of hydration inhibitors in transported gas is compared. Reduction of hydrate formation temperature in presence of a synthetic inhibitor has been proved.

Paper [14] presents the concept of calculating condition parameters of gas transmission through a network of gas collection from wells. The grid computing method was used. At the same time, heat exchange between the transported gas and the external environment, in particular the longitudinal heat exchange at each of the sections of the pipeline network mentioned in [8] is not taken into account. The problem of plug and hydrate formation in a pipeline is not considered as well.

The authors of work [15] suggest the use of low-potential heat for gas-producing wells and productive gas-bearing floors. The problem of optimizing generation of electric energy by the criterion of the number of wells taking into account the well bottom temperatures and heat exchange between wells and wall rocks was solved. In this case, the Rankine cycle was taken as a theoretical basis for calculation of heat engines with distributed parameters.

Total energy consumption of trunk gas transmission for a multi-strand net including compressor stations, sections of heat exchange with environment, bridges and branches was calculated in [16]. Energy costs for compression were minimized. Heat dissipation from the gas heated at compressor stations was taken into account.

A hierarchical model based on one-dimensional isothermal Euler equations of fluid dynamics is used in work [17] for modeling and optimizing gas flows in a pipeline network. The strategy of adaptive modeling consists in the use of one complete and two simplified Euler equations. It was established that simplification of the Euler equation to the level of algebraic equation makes the relative error 3.5 times higher and partial simplification makes it 2.5 times higher.

A method of reverse calculation of heat flow in a network was developed in [18] based on the analysis of topological structure of the heat network, its hydraulic and thermodynamic parameters. The method is applicable to a typical radial heating network (electric and thermal room heating model) which contains a thermoelectric unit, an electric boiler, and other elements. For such a combined electrothermal system, an optimal (by total thermal energy consumption) calculation method was realized. Its accuracy and feasibility were checked on a physical model. It was shown that taking into account the external influx of heat to the pipeline sections minimizes the overall heat consumption and improves control of the processes of fluid transportation in pipeline networks.

As shown in [19], at a temperature of 40 °C for heat carrier and 10 °C for ground, average coefficient of performance (COP) for heat ground pumps of ground-coupled thermal pump (GCTP) type reaches 5 units. This confirms feasibility of using low-potential heat of ground bodies around the buried pipelines including gas pipelines with temperature of hydrate formation below –30 to –40 °C. The value of COP depends on the temperature gradient "transported gas – environment" at the entrance to the heat exchange loop. However, the above gradients are not considered separately in [19].

Simulation and analysis of natural gas transmission by the 24-inch main pipeline Amenam-Kpono, Delta Niger (Nigeria) were performed in [20]. The operating parameters including pressure, temperature, density, flow rate and dew point for gas were determined. It was recommended to take into account simultaneously the action of inhibitors and the actual change of transportation parameters in order to prevent hydration in the process of gas transmission in pipelines. For prophylactic purposes, gas temperature is maximally increased and pressure decreased to possible limits.

A model of predicting thermodynamic parameters of natural gas in a pipeline was developed in work [21]. Convergence of the model experimental data with field experimental data was demonstrated. Heat exchange between sea water and transported gas in a section of flexible gas pipeline was considered. The fact of increase in the gas temperature from the initial to the final section of the pipeline (at water temperature in the sea higher than temperature of the incoming gas flow) has been recorded but its scientific analysis, in particular, the influence on hydrate formation, has not been made.

Thus, the methods of network simulation and anti-hydration methods presented in works [13–23] include the use of thermophysical and physicochemical effects, in particular, thermal pumps and boilers, the effect of thermal pump and direct heating, housings and heat-insulating effects, change of thermobaric conditions of transportation. The principles of mathematical modeling in a number of papers, in particular in [19–24], solve a broad class of production problems. At the same time, the concept of controlling the processes of natural gas transmission in networks with consideration of the thermal pump effect was not worked out. Most studies are aimed at reduction or stabilization of heat losses in gas transmission networks. The possibility of increasing the total energy in multi-strand systems with branches and bridges with the help of gas-dynamic thermal pumps is not described in detail or analyzed. In particular, the latter is extremely important for inter-field transportation networks (near the places of production and the places of consumption) where there are major risks of plug and hydrate formation [20, 21, 24–26].

3. The aim and objectives of the study

This work objective was to substantiate the possibility of using thermal pump effect in the pipeline sections of the gas transmission network to prevent plug and hydrate formation.

To achieve this objective, the following tasks were set:

– quantitatively assess the degree of environmental impact on the thermobaric mode of gas transfer taking into account the Joule-Thomson effect to develop an empirical formula for calculating the nonstationary process of gas transmission upstream and downstream the bridge;

– determine the coefficient of performance (COP) for the network system of a multi-strand pipeline equipped with thermal pumps;

– formulate the principles of constructing the topology of the flow diagram of a multi-strand gas pipeline with bridges and branches which provides a minimum risk of plug and hydrate formation due to the use of the thermal pump effect.

4. Materials and methods used in the study of the use of a thermal pump effect in gas pipeline nets

This study used the methods of mathematical modeling of gas transportation in pipeline networks, processes of heat exchange between gas and environment, gas throttling with transformation of potential energy into thermal energy, differential and integral calculus.

In particular, the following was used:

– the theory of graphs for structured mathematical modeling of gas pipeline network systems;

– the methods for calculating parameters of gas pipeline network systems [21, 22], in particular, Runge-Kutt method of the fourth order and the quasi-Newtonian method for solving systems of nonlinear equations;

– the method of electrohydraulic analogy for the use of mathematical tools of description of electric systems in the description of gas pipeline network systems;

– the method of nodal potentials and contour currents.

5. Results of analytical studies of the thermal pump effect in gas pipeline systems

To quantitatively assess the degree of environmental impact on the temperature conditions of the gas transmission process, develop a mathematical model of transportation with longitudinal heat exchange for multi-strand pipeline systems of a network type. To that end, present the pipeline system in the form of a graph (Fig. 1). The nodes are marked with an asterisk (*) next to the number. The branches are numbered with Arabic numerals and contours with Roman numerals. There may be a source of additional pressure E and a hydraulic resistance Z on each of the graph branches corresponding to the sections of the pipeline. Consumers or gas source J can be connected parallel to the branches of the diagram.

Based on the diagram of gas flows, create a mathematical model taking into account the main gas-dynamic parameters and dependencies between them.

The mass gas flow rate depending on its velocity v, in the section of a gas line with the cross-section S is $M=vS\rho$. Given the Darcy equation

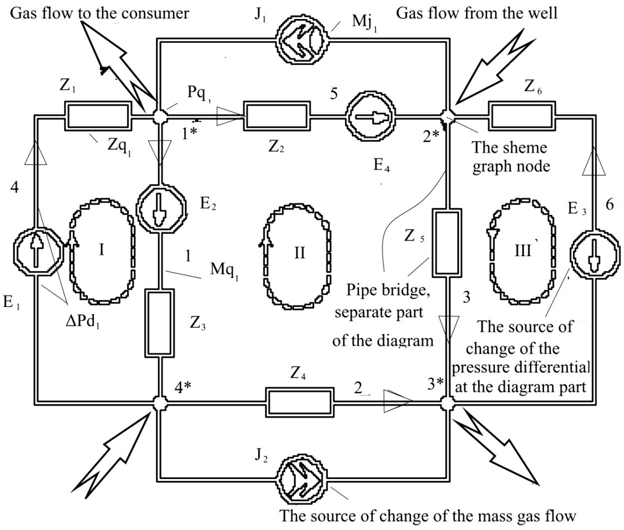
$$\Delta P=\lambda L v^2 \rho/2D \qquad (1)$$

and the gas state equation $P=\rho zRT$ for M, the graph of the calculation diagram of a multi-strand gas pipeline is obtained (Fig. 1).

A and B are matrices of crossings of the diagram contours; *E* is pressure matrix for the diagram branches; J is the gas flow matrix for the diagram branches, *Z* is the matrix of the *Zq* parameter for the diagram nodes; I, II, III are contours of the diagram; 1, 2, 3 are branches of the diagram; 1*, 2*, 3* are the diagram nodes; J_1, J_2 are gas sources (deposits, inflow from wells, etc.); E_1, E_2 are sources of pressure (compressors, pumps, heaters, etc.); Z_1, Z_2 are the ratios of pressure differential to gas flow.

$$M=\frac{\pi\cdot D^{2.5}}{4}\cdot\sqrt{\frac{2\cdot P\cdot\Delta P}{z\cdot R\cdot T\cdot L\cdot\lambda}}, \tag{2}$$

where λ is the coefficient of pneumatic resistance of the gas pipeline; *z* is the gas compressibility; *R* is the gas constant; *P* is the gas pressure; *T* is the gas temperature; *Re* is the Reynolds number, *L* is the gas pipeline length; *D* is the gas pipeline diameter; ρ is the gas density; *S* is the area of cross section of the gas pipeline; *v* is the gas velocity.



$$B=\begin{pmatrix}1&0&0&1&0&0\\-1&-1&1&0&1&0\\0&0&1&0&0&1\end{pmatrix}\qquad A=\begin{pmatrix}1&0&0&-1&1&0\\0&0&1&0&-1&-1\\0&-1&-1&0&0&1\end{pmatrix}\qquad Z=\begin{pmatrix}Z_3&0&0&0&0&0\\0&Z_4&0&0&0&0\\0&0&Z_5&0&0&0\\0&0&0&Z_1&0&0\\0&0&0&0&Z_2&0\\0&0&0&0&0&Z_6\end{pmatrix}$$

$$E=(E_2\ 0\ 0\ E_1\ E_4\ {-E_3})^T\qquad J=(0\ {-J_2}\ 0\ 0\ J_1\ 0)^T$$

Fig. 1. Example of graph of a multi-strand gas pipeline diagram

To simplify recording of the mathematical model equations, perform the following parameter replacement. Square the right and the left sides of equation (2) and replace the parameter designations:

$$Mq=M^2,\ Pq=P^2,\ \Delta Pq=P_1^2\cdot P_2^2.$$

The following relations *Zq* and *Mq* are obtained:

$$Mq=\frac{\pi^2\cdot D^5}{16\cdot z\cdot R\cdot T\cdot L\cdot\lambda}\cdot\left(P_1^2-P_2^2\right)=\frac{\Delta Pq}{Zq}, \tag{3}$$

where the hydraulic equivalent of the electric resistance *Zq* is defined by the expression:

$$Zq=\frac{16\cdot z\cdot R\cdot T\cdot L\cdot\lambda}{\pi^2\cdot D^5}. \tag{4}$$

Calculation of the throttle effect and heating of sections in the multi-strand gas pipeline is based on the assumption of the throttling and heat-receiving sections of the process diagram of the gas pipelines as separate branches of the graph of the corresponding diagram. In this case, the network calculations are carried out using gas-dynamic parameters *Pq, Mq Zq,* Δ*Pd* (Fig. 1).

Turn from the system of equations for calculating network parameters known in electrical engineering and hydraulics [16, 18, 22] to a new system of equations of the mathematical model of pneumatic parameters taking into account (1)–(4), the known method of nodal potentials. This makes it possible to obtain a mathematical model in the form of a system for a multi-strand gas pipeline of a network type with a stationary mode of gas transmission in a matrix-functional form:

$$\begin{cases}A\cdot Zq^{-1}\cdot A^T\cdot Pq(A,Zq,\Delta Pd,Mj)=\\=A\cdot Mj-A\cdot Zq^{-1}\cdot\Delta Pd,\\Mq(A,Zq,\Delta Pd,Mj)=\\=Zq^{-1}\cdot(\Delta Pd+\Delta Pq(A,Z,\Delta Pd,Mj))-Mj,\\\Delta Pq(A,Zq,\Delta Pd,Mj)=A^T\cdot Pq(A,Z,\Delta Pd,Mj),\\\Delta Pq(A,Zq,\Delta Pd,Mj)=Zq\cdot Mq(A,Z,\Delta Pd,Mj),\\Zq=\dfrac{16\cdot z\cdot R\cdot T\cdot L\cdot\lambda}{\pi^2\cdot D^5},\\M=Mq(A,Zq,\Delta Pd,Mj)^{0.5},\\P=Pq(A,Z,\Delta Pd,Mj)^{0.5},\end{cases} \tag{5}$$

where Δ*Pd* is the sources of potential energy of pressure in the sections (connected in series with *Z*); *Mj* is the matrix of mass gas flow of the sources of input and output gas flows (in sections of the diagram, they are connected parallel to the branches); *Mq* is the mass flow rate of gas in the section of the branch (squared); *Zq* is the ratio of the difference of squares of pressure to the square of mass flow, $((P^2\text{-}P^2)/M^2)$; *Pq* is square of gas pressure at the node; Δ*Pq* is the difference of the squared pressures in the branch.

For non-stationary processes, the complete equations of motion, continuities and energies of the gas flow were used. Relations between the gas mass flow, temperature, pressure, hydraulic resistance and gas density were obtained on the basis of the Euler equation in a form of a system of gas-dynamic equations (6). The system of the mathematical model equations [17] was revised with allowance for the adjustment coefficients and the unit conversion factor K1, K2, K3. After simple transformations, a modified system of differential equations in partial derivatives was obtained and used for network calculations (6). At the first stage, the initial conditions for the stationary transmission of gas through the network were formed and the analytical dependencies (1)–(5) were used in the calculations. Next, a simplified system of equations (6) of a non-stationary non-isothermal motion of a real gas in a section of a branched gas pipeline was used. It consists of equations of motion, continuity and the energy of a gas flow. The system of equations (6) includes the dependences of the gas compression coefficient (z), gas density (ρ), the Joule-Thomson (Dj) coefficient, the gas heat capacity (Cp), viscosity and hydraulic resistance (λ) on the gas parameters, the geometric and operation parameters of the gas pipeline system and has the form:

$$\begin{cases} \dfrac{1}{z(P,T)RT}\cdot\dfrac{\partial P}{\partial t}+\dfrac{w}{z(P,T)RT}\cdot\dfrac{\partial P}{\partial x}+\rho(P,T)\cdot\dfrac{\partial w}{\partial x}- \\ -\dfrac{K_1\rho(P,T)}{T}\cdot\dfrac{\partial T}{\partial t}+\dfrac{1}{S}\cdot dG_{\text{к}}(x_{\text{в}},t)=0, \\ \dfrac{1}{\rho(P,T)}\cdot\dfrac{\partial P}{\partial x}+\dfrac{\partial w}{\partial t}+2\cdot\alpha\cdot w\cdot\dfrac{\partial w}{\partial x}+(1+\alpha)\cdot\dfrac{w^2}{P}\cdot\dfrac{\partial P}{\partial x}+\dfrac{\lambda(P,T,w,k_e)\cdot w^2}{2\cdot D}=0, \\ c_p(P,T)\cdot\left(w\dfrac{\partial T}{\partial x}+\dfrac{\partial T}{\partial t}-K_2\cdot D_j\cdot(P,T)\dfrac{\partial P}{\partial x}\right)+\dfrac{4\cdot K\cdot\ln(T-T_0)}{\rho(P,T)\cdot D}+K_3\dfrac{k-1}{k}\dfrac{w}{R}\dfrac{\partial w}{\partial t}=0, \\ P=\rho\cdot z(P,T)\cdot R\cdot T, \\ c_p(P,T)=1695+1{,}838\cdot T+\dfrac{1960\cdot(P-10^5)}{T^3}, \\ D_j=9{,}26\cdot10^{-3}\dfrac{\Delta^{1{,}3}\cdot R\cdot T^{0{,}7}}{(P_1-P_2)}[\ln(1695+1{,}838T+1960\cdot T^{-3}\cdot P_1), \\ -\ln(1695+1{,}838T+1960\cdot T^{-3}\cdot P_2)], \\ z(P,T)=1-5{,}5\cdot\dfrac{\Delta^{1{,}3}}{T^{3{,}3}}\cdot P, \\ \lambda(P,T,w,k_e)=0{,}067\left(\dfrac{158}{\mathrm{Re}(P,T,w)}+\dfrac{2\cdot k_e}{D}\right)^{0{,}2}, \\ \mu(P,T,M)=\dfrac{(9.41+0.02\cdot M)\cdot(1.8\cdot T)^{1.5}}{(209+19\cdot M+1.8\cdot T)\cdot10^7}\cdot EXP\left[\left(3.5+\dfrac{547.8}{1.8\cdot T}+0.01\cdot M\right)\times\right. \\ \left.\times\left(\dfrac{P\cdot10^3}{Zskv(P,T)\cdot\dfrac{8314.3}{M}\cdot T}\right)^{\left[2.4-0.2\left(3.5+\frac{547.8}{1.8T}+0.01\cdot M\right)\right]}\right], \end{cases} \tag{6}$$

where μ (*P*, *T*, *M*) is dynamic viscosity; *P* is pressure; *T* is temperature; *M* is molar mass; k_e is equivalent internal roughness of the pipeline wall; *w* is the averaged in the cross section flow rate of the gas; *D* is diameter; *Re* is the Reynolds number; x_B is longitudinal coordinate; t_B is time; *To* is temperature of ground and rocks near the pipeline; G_x (x_B, t_B) is mass flow rate in the branch; K_1, K_2, K_3 are coefficients that take into account dimension and analytical simplifications.

Thus, the quantitative assessment of the degree of environmental impact on the temperature conditions of gas transmission with longitudinal heat exchange for multi-strand branched pipeline systems of a network type can be accomplished using systems of equations (5) and (6).

Based on the correlation analysis of real production data of the main gas pipelines of the Shebelynka-Dnipro-Odesa gas pipeline, an empirical formula for calculating the Joule-Thomson effect for a non-stationary flow in the pipeline section before and after the bridge has been derived:

$$D_j=9{,}26\cdot10^{-3}\frac{\Delta^{1{,}3}RT^{0{,}7}}{(P_1-P_2)}\times \times\begin{bmatrix}\ln(1695+1{,}838T+1960\cdot T^{-3}P_1)- \\ -\ln(1695+1{,}838T+1960\cdot T^{-3}P_2)\end{bmatrix}. \tag{7}$$

This formula was obtained in the following range of sampling: the relative gas density by air Δ=0.56–0.66; the gas constant of a mixture of natural gases *R*=460–490 J/kg·K; work pressures P_1 and P_2=0.3–7.5 MPa; temperature *T*= =273–300 K and included in the system of equations (6).

A characteristic feature of the nonstationary motion of gas in industrial gas pipeline systems is localizing in time and space. For example, calculation by formulas (5), (6) shows that the sudden change in mass flow by 25 % in a 1 km long pipeline bridge (Fig. 2, *a)* causes pressure variation by 0.05–0.1 % (absolute value) which lasts up to 2 minutes (Fig. 2, *b*).

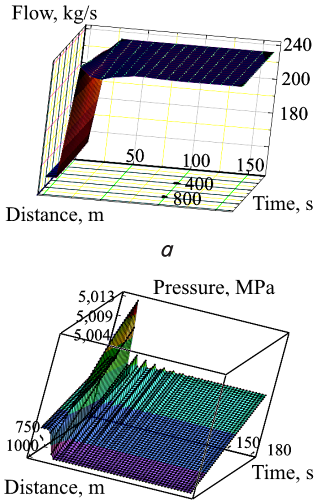


Fig. 2. Modeling of non-stationary processes in the inter-strand bridge of a gas pipeline system at a stepped change of mass flow of gas by 25 %: stepped change of mass flow of gas (*a*); the graph of gas pressure acceleration in the inter-strand bridge (*b*)

To determine the integral coefficient of transformation of the net system of a multi-strand pipeline equipped with thermal pumps using the models (5) and (6), the heat obtained at the gas transmission sections and the work performed by the gas-dynamic drive of the pipeline system were determined, the total energy of the diagram sections (1–6 in Fig. 1) was determined in the first stage. It varies at diverse loadings and ambient temperatures. Next, comparison of the total energy taking into account the thermal pumps working in some sections and with no thermal pumps in other sections was made. The coefficient COP of the multi-strand gas pipeline was defined as the ratio of the total energy of the system sections to that spent for the thermal pump operation.

The principles of constructing the topology of a multi-strand gas pipeline with bridges and branches which ensure a minimal risk of plug and hydrate formation consist in activation and regulation of energy transformation and the heat exchange processes in the pipeline sections. Specificity (distributed parameters), multicomponent nature and multivariant gas flow paths in a multi-strand pipeline as an object of regulation determined the following steps of constructing a rational diagram topology:

1) analysis of the diagram and localization of critical sections under the conditions of plug and hydrate formation;

2) determination and localization of the controllers of the operation parameters of gas transmission which are located closest to the critical sections and realize the thermal pump effect;

3) estimation of heat-contributory sections according to the energy potential of the thermal pump effect;

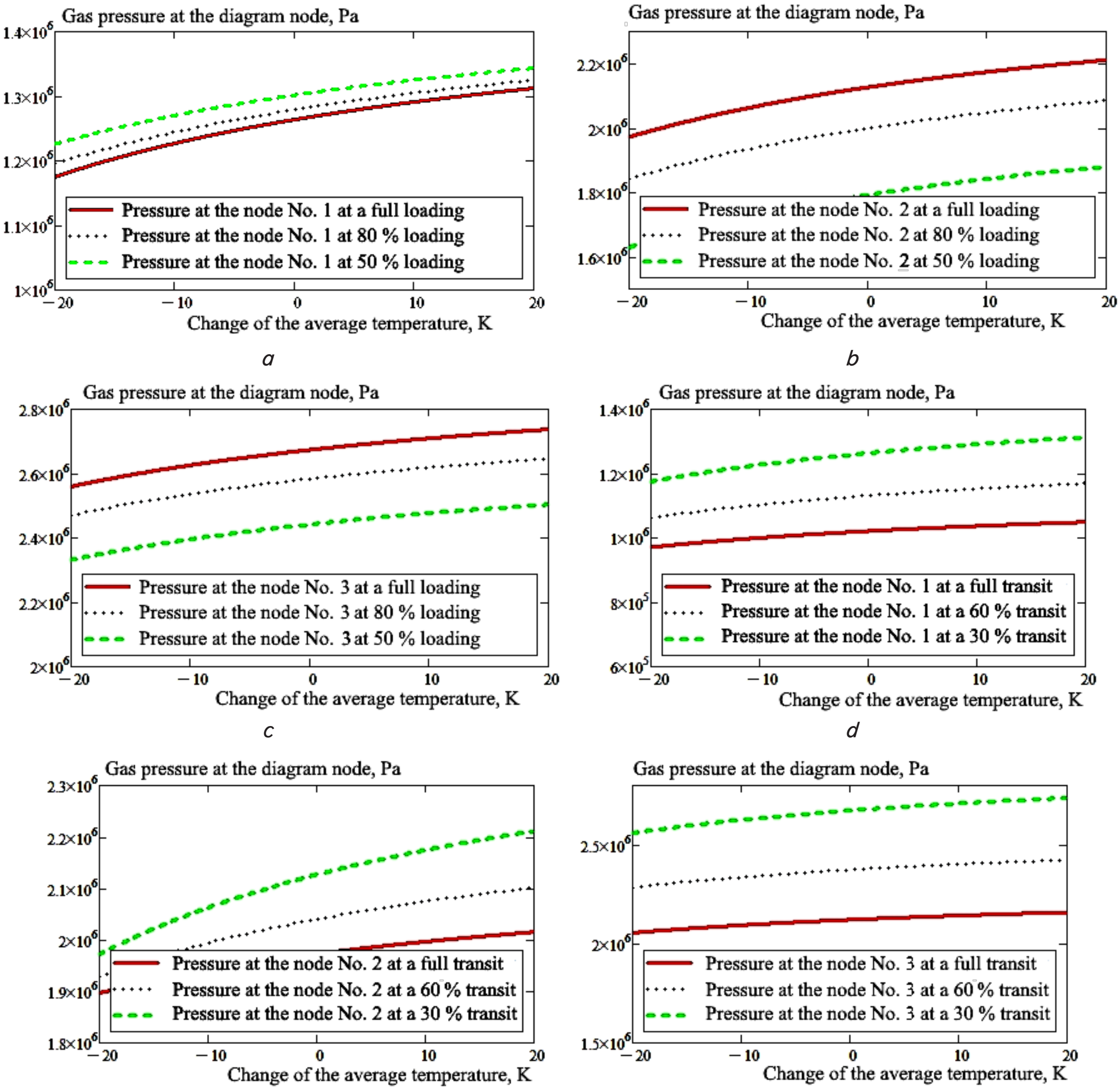
4) drawing up a flow diagram with an effective topology for a maximum use of the thermal pump effect in order to prevent and eliminate plug and hydrate formation;

5) verification for proximity to and bordering with critical temperatures of plug and hydrate formation.

6. Discussion and analysis of the results obtained in the study of the thermal pump effect in gas pipelines

Verification of the constructed mathematical model (5) and (6) and testing the principles of schematic design of the use of the thermal pump effect through regulation of gas flows in the network was carried out with the help of the Mathcad software. As a basis for calculations, a typical topology of municipal net of gas supply from the high-pressure trunk to the gas distribution stations of a medium pressure for consumers. The average length of the calculated section was taken equal to 20 km. According to the meteorological observatories in Ukraine, fluctuations of ground and surface water temperatures averaged for seasons in central and eastern Ukraine were from 0 to 17 °C (±0–20 °C range was taken in calculations).

A family of graphs of dependence of pressures in the nodes of the pipeline system which corresponds to the basic diagram topology was obtained from the change in gas temperature in the diagram sections (Fig. 1). Note that the gas temperature in the diagram sections correlates with the ambient temperature (Shukhov equation). The results were obtained in conditions of changes in loading of compressors, loading in transit and the volume of internal gas consumption (up to 2–3 times), which is typical for many Ukrainian cities. The range of gas pressures was 3–4 MPa, the mass flow of gas through the pipelines was less than 15 kg/s. Length of sections was up to 30–50 km. Diameter of pipelines was up to 300 mm. Figure 3*a-e* shows the degree of environmental impact on the thermobaric mode of further gas transmission. The graphs were obtained for the diagram nodes of the consumption lines No. 1–3 and the line of gas supply, node No. 2, with internal loading of 50; 80; 100 % and transit loading of 30; 60; 100 %.



a *b* *c* *d* *e* *f*

Fig. 3. Dependence of gas pressure in the nodes of the gas transmission system from the change in temperature of gas for various transit and consumer loadings: for the 3rd node (*a, d*); for the 2nd node (*b, e*); for the 1st node (*c, f*)

Analysis of the obtained results (Fig. 3) shows that increase in transit loading and reduction of internal loading of the system increases influence of temperature change on pressure. Reducing transit loading and increasing internal consumption in the conditions of seasonal fluctuations of temperature of adjacent ground bodies (or local reservoirs) causes a 3-to-4 time change in pressure at the exit from the system. In this case, temperature gradients reach ±0–20 °C.

As can be seen from Fig. 3, *a–c*, fluctuation of the ground temperature causes pressure change in the nodes of the system which is influenced by loading of the pipeline by internal consumers (the gas field and nearby settlements). For example, as shown in Fig. 3, *a*, for the 3rd node, the change in temperature of the ground bodies within ±10 °C at a 50 % internal loading of the pipeline causes pressure change within 5 %. It is evident from Fig. 3, *b* that pressure at the node 1 varies by 3–4 % with temperature change of ±10 °C. With an increase in transit loading from 30 % to 100 %, even greater changes in pressure occur depending on the temperature change (to 6–7 % in Fig. 3, *d*). It is evident from Fig. 3, *f* that when temperature in node No. 1 having the smallest pressure changes by ±10 °C, pressure changes by 10–15 %.

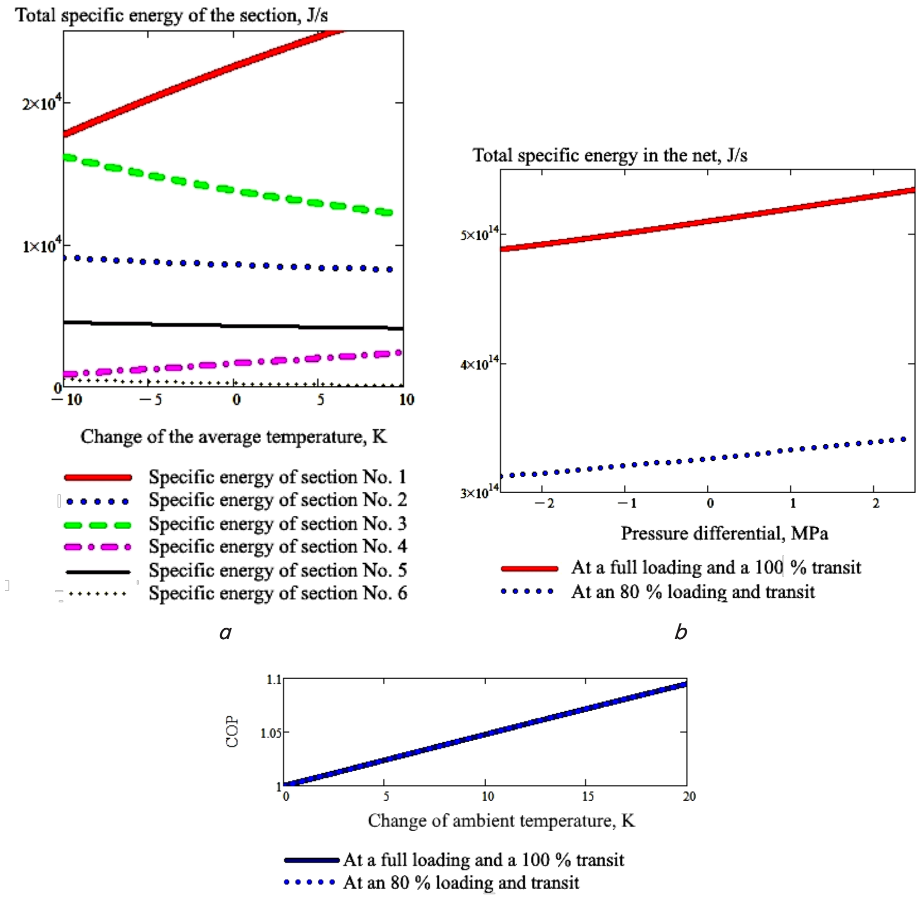
Formula (7) for the Joule-Thomson coefficient was derived based on the classical formula [10] by applying empirical formulas for heat capacity [23], the coefficient of natural gas compressibility [26] and the Mendeleev-Clapeyron law. Our studies [23] have shown that calculation of the Joule-Thomson coefficient by formula (7) improves accuracy of Dj estimate by 15 % compared with the empirical formula of the current standard [2].

To determine integral coefficient of transformation of the net system of multi-strand pipelines including thermal pumps, the heat generated in the gas transmission sections and the work performed by a gas-dynamic drive of the pipeline system were determined with the use of models (5) and (6). At the first stage, total energy of the diagram sections (1–6 in Fig. 1) was determined. It changed with the change of loading and ambient temperature. After that, the total energy of the sections equipped with thermal pumps was compared with the total energy of the sections without thermal pumps. The integral coefficient of transformation of a multi-strand pipeline network system was defined as a ratio of the total energy of the system sections to the energy spent on operation of thermal pumps. The gas-dynamic drive of thermal pumps consumes potential energy of pressure spent directly in the pipelines.

Fig. 4 shows dependence of the change of specific energy for 6 sections of the topological diagram of the calculation example (Fig. 1) on the temperature change at the throttling devices found by using formula (7) (Fig. 4, *a*). As can be seen from Fig. 4*a*, the total specific energy at individual sections of the diagram increases or decreases as a balance redistribution of energies occurs as a result of temperature effects and artificial throttles. For example, the graph of section No. 1 shows an 18 % increase in energy of this section when temperature changes by 5 °C. For the graph of section No. 3, there is a 14 % decrease in energy when temperature changes by 5 °C.

Fig. 4, *b* shows the change of total energy of the network system depending on the variation of pressure differential on the throttling devices. When the pressure differential at the active gas pipelines changes by 2–2.5 MPa, the total energy in the network system changes by 7 %. The thermal pump effect and reduction of pressure by artificial throttling devices cause growth of total energy by the mentioned percentage.

Fig. 4, *c* shows dependence of COP on fluctuation of the gas temperature relative to the average annual seasonal temperature. It is clear from the graph that COP approaches 1 at temperatures close to 0 °C in the winter. The COP can reach 1.05–1.07 in the summer, autumn and spring periods (ground temperature reaches 17–18 °C at the depth of gas pipelines).



a

b

c

Fig. 4. Result of calculating the specific energy in the sections, total specific energy and COP in the net gas pipeline system when using artificial throttling devices to intensify the thermal pump effect: dependence of the change of the specific energy in 6 sections of the topological diagram of the calculation example depending on temperature variation at the throttling devices (*a*); change of the total energy of the network system depending on the pressure differential on the throttling devices (*b*); dependence of COP on the gas temperature fluctuation relative to the average annual seasonal temperature (*c*)

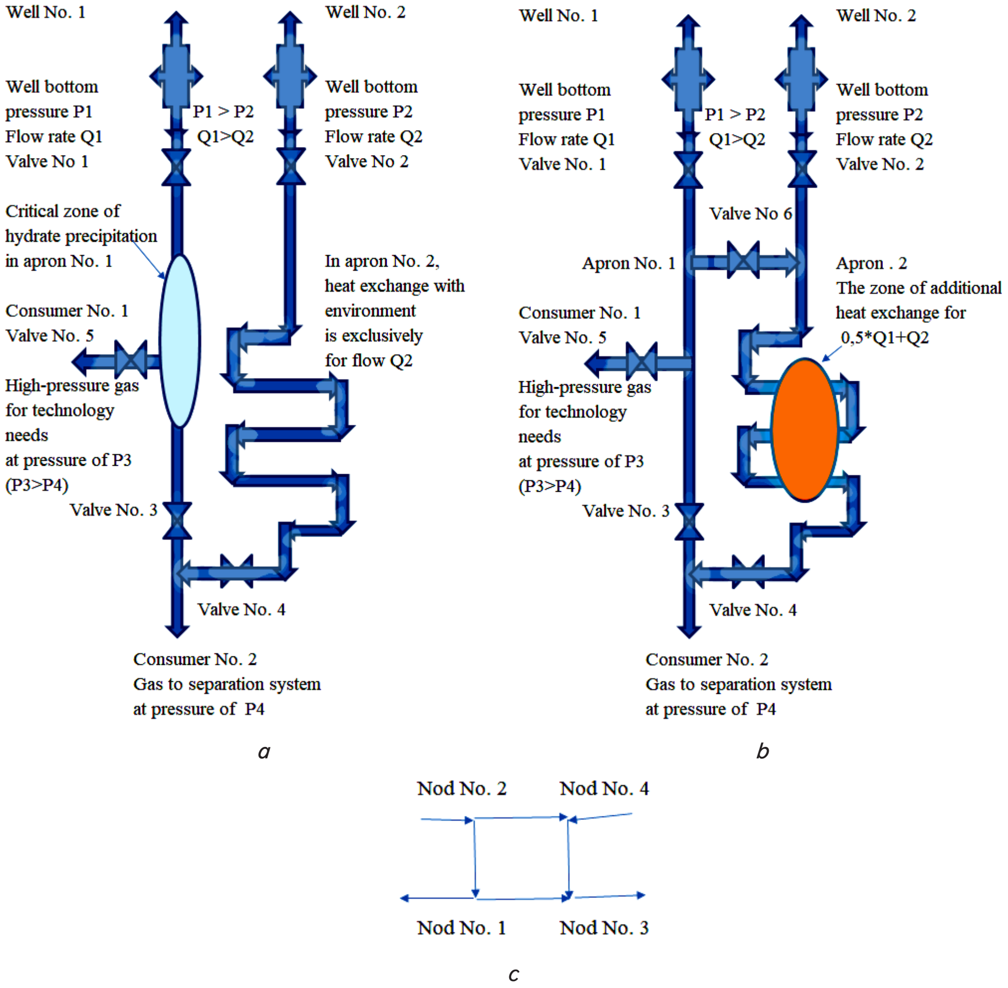
The principles of constructing the topology of a multi-strand gas pipeline with bridges and branches which provide the minimum risk of plug and hydrate formation consist in introduction of throttling devices and heat-exchange sections into the process diagram. The latter are located downstream the throttles. Effective length of the sections heated from the low-potential heat of adjacent ground should be taken into account. The developed principles ensure an advantageous use of the thermal pump effect in the gas transmission systems. At lengths of gas pipeline sections larger than 10–15 km and pipeline diameters of 0.2–0.5 m, COP of formed and actuated gas-dynamic thermal pumps can reach the value of 1.1.

An example of the gas collection systems of the Senoman fields of the Urengoy deposit [25] shows that plug and hydrate formation begins at critical temperatures of −2 °C and pipeline lengths more than 3.7 km. From the data that we have (Fig. 2, 3) it follows that the schematic use of thermal pumps reduces the critical temperature of hydration by 8–10 °C. According to [25], reduction of the critical temperature of hydrate formation by 5 °C increases the distance of hydrate-free transportation to 9–10 km.

The engineering solution of the gas-dynamic thermal pump based on the above-mentioned simulation results was implemented within the frames of experimental-industrial implementation at the Yuliyivsky oil-and-gas condensate field (Ukraine). Fig. 5 shows the diagrams of industrial gas collection from wells. As shown in Fig. 5, *a*, a critical zone of hydrate precipitation is formed in the apron pipeline No. 1 during the winter period which is determined by pressure, temperature and humidity of natural gas. Fig. 5, *b* shows the introduced gas-dynamic thermal pump with valves No. 1–6 and the heat-exchange loop of the apron No. 2 (absence of valve No. 6 and the corresponding bridge between the aprons render impossible use of such thermal pump in Fig. 5, *a*).

As demonstrated in Fig. 5, *a*, pressure is only reduced (in one step) by the valve number 1 and the resulting sharp decrease in temperature leads to formation of a critical zone of hydrate precipitation in the apron of well No. 1. The diagram of Fig. 5, *b* reduction of gas pressure at well No. 1 occurs in two steps at valves Nos. 1 and 6. In this case, the thermal pump effect for gas of wells Nos. 1 and 2 manifests itself in the apron No. 2. Thus, in the case of the implementation of the diagram by the variant with a two-step reduction (Fig. 5, *b*), a part of gas from well No. 1 is by-passed through valve No. 6 to the heat-exchange zone of the apron of well No. 2.

Fig. 5, *c* shows the graph of the diagram of gas flows from wells Nos. 1 and 2 which is analogous to the generalized graph of the model shown in Fig. 1. Calculation of the operation parameters of the gas transmission system was made for this graph with the use of the system of equations (5), (6). The results of the comparative analysis of the operating heat and hydraulic parameters of gas transmission by the aprons of the wells Nos. 1 and 2 for the variants *a* and *b* (Fig. 5) in conditions of simulation and industrial experiment are shown in Table. 1.



a *b*

c

Fig. 5. Process flow diagrams and the diagram graph in implementing the industrial experiment: without a gas-dynamic thermal pump (*a*); with a gas-dynamic thermal pump (*b*); the diagram graph (*c*)

Table 1

Results of comparative analysis of operating heat and hydraulic parameters of gas transmission by aprons of wells Nos. 1 and 2 under the conditions of simulation and full-scale industrial experiment

Diagram variant No.	Gas flow, m^3/day		Average pressure, MPa		Gas temperature at the valve exit, K		Average apron temperature, K	
	Apron No. 1	Apron No. 2	Apron No. 1	Apron No. 2	Valve No. 1	Valve No. 2	Apron No. 1	Apron No. 2
Fig. 5, *b*, experiment	42 (0.5Q1)	(Q2+0.5Q1) 67	1.55	0.95	262	266	260	278
Fig. 5, *a*, experiment	84 (Q1)	(Q2) 25	2.41	0.95	256	262	257	271
Fig. 5, *b*, simulation	42 (0.5Q1)	(Q2+0.5Q1) 67	1.55	0.95	263	268	259	281
Fig. 5, *a*, simulation	84 (Q1)	(Q2) 25	2.41	0.95	255	261	258	273

It is seen from Table 1 that the average gas temperature in apron No. 1 after valve No. 1 during operation of the gas-dynamic thermal pump increased from 257 K to 260 K (model data were 258 and 259 K, respectively). Pressure in apron No. 1 after valve No. 1 during operation of the gas-dynamic thermal pump decreased from 2.41 to 1.55 MPa. This makes it possible to move away from the thermobaric point of hydration to a safe zone. Consequently, the full-scale industrial experiment has shown and the model calculation confirmed that the critical zone of hydration in the apron of well No. 1 disappears if the thermal pump effect is applied.

The implemented engineering solution and the use of the developed mathematical model in the given industrial experiment made it possible to reduce by 75 % the costs of the hydrate formation inhibitor in well No. 1. Methanol is conventionally used as a hydrate-forming inhibitor for the Yuliyivsky oil-and-gas condensate fields. One ton of methanol was pumped into the well twice a week. After the implementation of the engineering proposal, this consumption was reduced to 0.5 t/week. Economic effect of industrial implementation was USD 1,100 per week.

Deviation of the results obtained in calculation using the developed model and the actual measurements (Table 1) was 1.5–1.7 % based on the average temperature in apron No. 2 (after gas passage of the zone with an active heat exchange). This deviation was obviously obtained because of impossibility of more accurate establishment of coefficient of heat exchange (parameter K in the second equation of the equation system (6)) between gas in the apron and the surrounding ground than it was established using the model with filled-up ground (with the ground samples taken).

7. Conclusions

1. It has been established that the change of ground temperature by ±10 °C in the 20 km long gas transmission sections of multi-strand pipeline system can cause a change of gas pressure within 5–15 %. The degree of influence of the ground temperature on the transported gas pressure is directly proportional to the transit and internal loading of the pipeline system. The theoretical-empirical formula for determining the Joule-Thomson coefficient that was derived enables estimation of the thermal pump effect on the energy and thermobaric parameters of the nonstationary gas transition processes.

2. Depending on the ambient temperature (0–20 °C), the integral coefficient of performance (COP) for the multi-strand pipeline network system (6 sections 7 to 43 km in length) which included gas-dynamic thermal pumps varied within 1.00–1.09. The principles of constructing topology of a multi-strand gas pipeline with bridges and branches which will ensure a minimum risk of plug and hydrate formation include activation and regulation of the energy-transforming and heat exchange processes in individual sections of the gas pipeline. This is achieved by introduction of additional throttling devices in front of bridges and branches of the pipeline system and checking for proximity to critical temperatures of plug and hydrate formation.

In further studies, it is expedient to broaden analysis of the prospects of using the thermal pump effect for heating of fuel lines, in particular, oil, condensate, and water-coal fuels [26, 27].

Acknowledgments

The authors appreciate deeply the valuable methodological advice on calculation and presentation of the study results kindly rendered by Mr. A.O. Krut', Dr. Tech. Sc., Director of UKRNDIPROEKT Institute (Kyiv, Ukraine).

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