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Developing measures to eliminate of hydrate formation in underground gas storages

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ABSTRACT

Purpose: The objective of this article is the analysys of methods for preventing and eliminating hydrates formations, classifying them and choosing the best ones for use in underground gas storage facilities. Comprehensive measures for the stable operation of gas storage facilities in the presence of conditions for the occurrence of hydrates formations were developed. Zones, being potentially prone to the hydrates formation during the gas storage facilities operation were identified.

Design/methodology/approach: The operational parameters of gas storage wells during gas withdrawal are analyzed. The identified wells were operated under difficult conditions due to the deposition of hydrates on the wellheads, in flowlines and process equipment of gas storage facilities. The places of the highest hydrates accumulation on underground gas storages were determined: from the bottomhole of wells to the gas purification unit of the gas gathering station. Hydrate-prone zones were identified by computational fluid dynamic (CFD) modeling at the location of regulating choke installations in underground gas storage facilities.

Findings: The zones of the greatest hydrates accumulation on underground gas storages were determined: from the bottomhole of wells to the gas purification unit of the gas gathering station. The analysis of the methods used in gas storage facilities of Ukraine to prevent and eliminate hydrates formation was out. A set of measures was proposed to prevent the hydrates formation in storage facilities to ensure their stable operation. Based on the Euler approach (Mixture model) by CFD modeling, zones prone to hydrates formation were determined at the installation site of regulating chokes in underground gas storages. The influence of the degree of fittings opening on the location of potential zones prone to hydrates formation was estimated.

The gas-dynamic processes in the internal cavity of the gas pipeline at the installation site of the control fittings were studied and their influence on the distribution of bulk particles of the gaseous and liquid phases was established. Based on the studies performed, it was recommended to change periodically the mode of well operation for a certain time by opening or closing the regulating choke under favorable conditions for the formation of hydrates, especially at low ambient temperatures.

Research limitations/implications: The obtained results of experimental studies and calculations showed that in order to solve the problem of hydrates formation at gas storage facilities, it is advisable to use diverse measures through the introduction of modern intelligent systems for monitoring and controlling the technological process. Further refinement of the algorithm of the proposed monitoring and control system with its approbation in production was provided.

Practical implications: The results of the experimental studies and CFD modeling carried out allowed providing a more reasonable approach to the application of various available methods and measures to prevent hydrates formation in underground gas storage facilities. This approach made it possible to develop new effective ways and measures to prevent such complication.

Originality/value: Based on the conducted experimental studies and modeling, the major zones prone to hydrates formation in underground gas storages were determined. The developed measures will allow timely detection and prevention of hydrates formation at gas storage facilities are original.

Keywords: Well, Flowline, Hydrates formation, Local constraints, Regulating choke

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ANALYSIS AND MODELLING

1. Introduction

One of the main problems typical for most underground gas storages (UGS) created in porous reservoirs is the presence of moisture in the gas stream. It is known that as a result of changes in thermodynamic conditions along the path of gas movement from the reservoir to the gas gathering station (GGS), solid crystalline compounds, hydrates, can be formed. They can be deposited on the inner surface of tubing from the bottom to the wellhead, in the X-mas tree of the well, in the flowline, both in straight sections and in local supports (bends, transitions, tees, welding joints, etc.), in pipelines and underground pipelines of the gas gathering station, valves, fittings, collectors, process equipment, etc. Most often, hydrates are formed in places where the gas flow is narrowed, for example, after the regulating choke (RC) at the installation of disconnecting devices of the gas gathering station.

The deposition of hydrates is accompanied by a decrease in the internal diameter of the pipeline, which leads to a decrease in the flow rate of individual wells and the productivity of the gas storage as a whole, and in some cases to the formation of a solid plug, which stops the movement of gas. Such complications negatively affect the possibility of ensuring the operation of wells considering the technological regime and, in general, the stable operation of the gas storage facility and the reliability of gas supply. Given the urgency of this problem, there is a need to study it in detail and determine the most effective measures to prevent this negative phenomenon.

2. Literature review

The problem of preventing hydrate formation arose simultaneously with the utilization of the first gas fields into industrial development and remains relevant at many gas industrial facilities. To solve it in practice, various measures are used, which are not always effective enough. In this regard, it is important to conduct a detailed analysis of this problem and develop comprehensive measures to prevent this phenomenon.

The phenomenon of hydrate formation was first noted in 1934 by the American scientist E.G. Hammershmidt [1]. He found that gas hydrates can form and accumulate in gas pipelines, causing them to block, and in some cases lead to emergencies. To solve the problem with hydrates in pipelines, the scientist provided the first recommendations on the use of inhibitors. Based on the results of many experimental data processing obtained for various inhibitors, E.G. Hammershmidt proposed an empirical formula for evaluating their effectiveness [2]

$$\Delta T = \frac{K \cdot X}{M \cdot (100 - X)}, \quad (1)$$

where

ΔT – decreasing the temperature of hydrates formation;

K – a constant that depends on the type of inhibitor;

X – inhibitor concentration, % (mass);

M – molecular weight of inhibitor.

In the 1930s-1950s, the American researchers Deaton and Frost, and later Katz and Kobayashi, made an important contribution to the research of gas hydrates. Deaton and Frost published a monograph devoted to the problem of preventing hydrate formation in gas pipelines, which presents experimental data on the phase equilibrium of gas hydrates of hydrocarbon gases (both for pure components and for mixtures). The cycle of these studies at the highest instrumental level was continued by Katz and Kobayashi et al. [3].

Due to experimental and theoretical studies of thermodynamics, physical and chemical properties of gas hydrates conducted by various scientists, several methods were developed for predicting the formation of hydrates (formation conditions, potential zones, accumulation rate, etc.). Based on numerous studies in world practice, many different methods for the prevention and elimination of hydrates were developed.

An auspicious guidance in resolving the question of hydrate formation is the development of new inhibitors that can be used both to prevent hydrate formation and to reduce corrosion.

In [4], a technology for the preparation of a complex inhibitor of hydrate formation and corrosion OV-07 was proposed, which makes it possible to protect effectively downhole equipment from corrosion and hydrate formation, especially in the absence of the possibility of supplying two separate inhibitors.

As is known from the world practice of the oil and gas industry, methanol is used as a reagent to prevent the formation of crystalline hydrates and the destruction of already formed crystalline hydrates. In particular, more than 10 thousand tons of methanol per year are used for this purpose in Ukraine. At the same time, methanol is an effective reagent in the implementation of natural gas production technology; it is characterized by high toxicity, fire hazard, and significant cost. Therefore, studies elaboration on the problem of partial or complete replacement of methanol is important and relevant [5].

In [6], a dynamic mathematical model was developed that can predict the time and place of hydrate formation in 90° bends during gas transportation through a pipeline using CFD modeling. For this purpose, 3D modeling of the bend was performed, which made it possible to determine potential zones prone to hydrate accumulation. The simulation results showed that hydrates are accumulated on the inner wall of the bend under conditions of low temperature and high pressure, and on-time lead to the gas flow blocking.

In [7], a model was proposed that can be used to simulate a multiphase flow and investigate the processes of hydrates formation. This model is implemented in the simulator. Based on the results of multiphase flow modeling, the zones of hydrate accumulation were determined.

In [8] a new model was developed concerning the interfacial interactions between a hydrated particle and a solid surface and between a hydrated particle and a hydrate surface. This model, just this one time, accounts for the premelting behavior of hydrate surfaces. It was shown that the adhesive forces between the hydrate particles and the pipe wall increase strongly when the surface of the pipe is more hydrophilic.

In [9] a gas hydrate formation and dissociation study were conducted on two multiphase piping systems containing gasoline, CO_2, water, and crude oil, CO_2, water, within the pressure range of 2.5-3.5 MPa with fixed water cut as 15% using gas hydrate rocking cell equipment. Using hydrate-liquid-vapor-equilibrium (HLVE) data, the phase diagrams for the system are constructed and tested to constitute the phase behavior in the polyphase pipelines. As well, studies on induction time and rate of gas hydrate formation were conducted for gasoline, CO_2, and water, and crude oil, CO_2, water systems. Using the assessment of phase behavior determined on the HLVE curve, the polyphase system with gasoline displays an obstruction in gas hydrates formation, as the HLVE curve shifts in relation to the lower temperature and higher-pressure region. The polyphase system including the crude oil system demonstrates a promotion of gas hydrates formation, as the HLVE curve shifted in relation to the higher temperature and lower pressure. In the same way, the kinetics of gas hydrate formation in the gasoline methodology is slow. Meanwhile, crude oil has a rapid gas hydrate formation ratio.

In [10] a CFD modeling was provided to predict the probability of hydrate formation in the gas pipeline. Results we got showed that the inlet and environmental temperatures are typically higher than the hydrate formation temperature, so the possibility of hydrate formation is low in the pipeline.

Additionally, the results obviously demonstrated that when we increase the gas flow rate or decrease the gas inlet temperature we can increase the possibility of hydrate formation in the pipeline.

3. Methods and materials

To determine the most effective methods for the prevention and elimination of hydrates, the possible places of their occurrence were analyzed using the example of the classical scheme of underground gas storage facilities. The classical scheme of gas flow to the gas storage facility during the withdrawal season implies a change in its thermobaric conditions from the reservoir to the outlet to the main gas pipeline. Gas from the productive horizon is supplied to the surface by a tubing column, and then by a flowline (gas pipeline), it enters the gas gathering station, where it is purified from mechanical impurities and liquid. Further, the gas is supplied for drying, metering, and compression, from where it is supplied to the gas pipeline to consumers.

When gas is filtered from the reservoir to the bottomhole, it is throttled in the perforation interval, accompanied by a decrease in its temperature. The magnitude of the temperature decrease depends on the filtration properties of the bottomhole formation zone, the quality of perforation, production rate, and thermobaric conditions. With a lack of perforation holes in the production string and high well productivity, a sharp decrease in the temperature of the gas flow and the formation of hydrates are possible.

Conditions for the formation of hydrates in the wellbore are determined by the temperature of the gas flow and pressure. Many factors influence the temperature of the gas moving in the wellbore: gas throttling in the bottomhole zone and the wellbore, heat exchange with surrounding rocks, gas friction against the tubing, condensation of water, and heavy hydrocarbons, etc. Due to the abundance of parameters that affect the gas temperature, as well as the lack of the ability to determine accurately some of them, the calculation methods for determining the temperature are not accurate enough. Therefore, the most accurate and complete information about the temperature distribution in the gas flow in a borehole can be obtained by direct measurement using temperature sensors.

When gas is moving by wellhead equipment (Xmas tree fittings and piping), the most likely places for the formation of hydrates are valves, bends, tees, coils, transitions, blind pipes, rock traps. For the conditions of ground sections of pipelines, hydrates formation is controlled by installing pressure gauges with a high accuracy class, which allows fixing the value of pressure and temperature.

Transportation of gas by industrial pipelines from the wellhead to the gas gathering station can be complicated by the deposition of hydrates in the internal cavity. In addition to the characteristics of the gas flow, the formation of hydrates in the pipeline depends on the profile of the gas pipeline, bends and branches, design, soil temperature, and heat transfer. In most cases, hydrates in gas pipelines are formed in the places of branches, transitions to a larger diameter, lower sections of the route, and aboveground sections. Also, hydrates can be deposited in hard-to-predict places of different sections of gas pipelines when the conditions for their formation are suitable.

At gas storage facilities, the greatest risk of hydrate formation occurs at the gas gathering station when gas is throttled by a regulating choke. This problem is typical for gas storage facilities, in which reservoir pressures significantly exceed the gas pressure in the main gas pipeline. In addition, hydrate formation at the GGS is observed in places where other local resistances are present.

At the GGS gas from wells is collected in a common collector and fed to a purification and drying unit. In the future, depending on the mode, the gas is compressed or flows by gravity to the metering unit and through the cross pipeline enters the main gas pipeline. After purification and drying the gas, the formation of hydrates in the gas storage is not observed.

A typical scheme of gas flow to the gas storage and more likely places for the formation of hydrates are shown in Figure 1.

Since natural gas hydrates are unstable chemical compounds, any deviation from thermodynamic equilibrium leads to their decomposition. However, if a thermodynamic equilibrium is maintained, accumulations of hydrates in the gas pipeline can remain for a long time. Therefore, to prevent timely the formation of hydrate accumulations, it is necessary to know the conditions for their appearance and to predict the places of their potential accumulations.

Depending on the place of hydrates formation, the most optimal ways of prevention and elimination are determined.

From practical experience, various methods for determining the location of hydrate deposition are known:

- in the well, hydrate deposits are determined by pressure decrease in the tubing space and growth in the annulus, as well as by a decrease in temperature at the wellhead;
- the deposition of hydrates in the gas pipeline section is determined by a change in pressure drop (growth). Based on the increase in the pressure drop, the occurrence of hydrate formation can be identified, but it is difficult to determine the exact place of their deposition;
- to clarify the place of hydrate deposition in the gas pipeline, a hole is drilled, a clamp with a pressure gauge

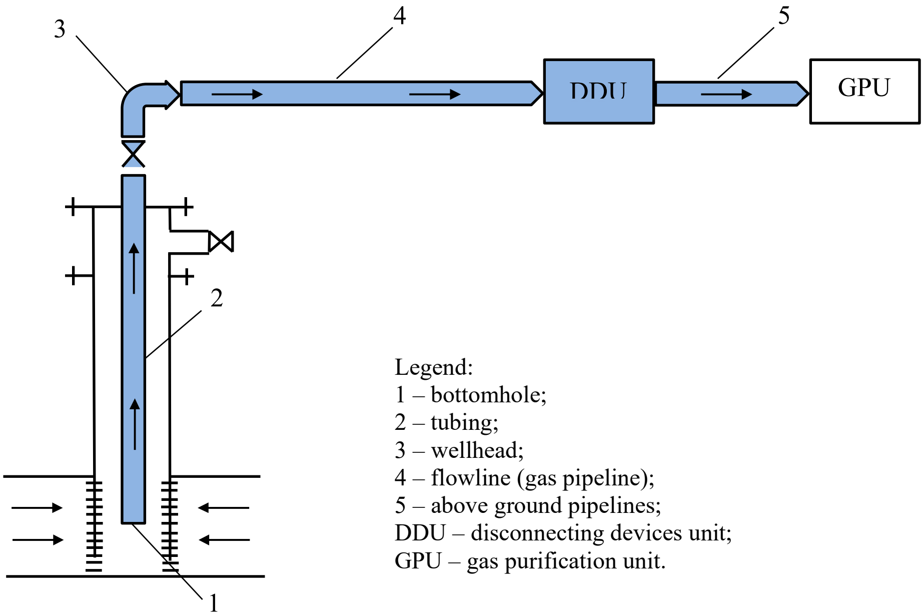

Fig. 1. Potential places of hydrates formation in gas storage (from bottomhole to gas gathering station)

is installed and the pressure is measured. Based on the results of pressure changes on the gas pipeline route, the place of hydrate deposition is determined;

- the place of hydrates accumulation is determined using the radar method. To do this, install antennas through a special hole in the internal cavity of the gas pipeline, which is later connected to a standard mobile radar station. The distance from the antenna to the place of hydrate formation is determined with an accuracy of several meters;
- to use different devices. For example, devices are known that determine the location of hydrate formation by pipes radio examination, and the like.

To ensure the reliable operation of wells and other technological equipment at gas storage facilities, their operation parameters (pressure, temperature, productivity) are monitored throughout the entire gas flow area. This allows controlling the operation mode of wells of technological equipment and wells and identifying emerging complications timely.

It should be noted that well production contains formation and condensate water, which can lead to such complications as fluid accumulation and hydrostatic formation, which negatively affect well performance. In this regard, gas storage engineers monitor the actual values of pressure and temperature to identify possible complications.

Taking into account many factors influencing the process of hydrate formation, it is advisable to build an effective model for preventing hydrate deposition and the possibility of controlling this process. This requires constant real-time monitoring of key thermobaric parameters. Given the nature of the various factors variability, the task of controlling and preventing hydrate formation in pipelines is very difficult. First of all, this is due to the lack of an adequate model for controlling the hydrate formation for a specific technological process.

For gas storage conditions, the following methods to prevent and eliminate hydrate formation are mostly used:

- heating of regulating fittings at the gas gathering station with an electric heating cable;
- periodical supply of methanol with the help of metered pumps with GGS inhibitor pipelines at the wellhead and in the flowline;
- periodic supply of methanol using pumps with GGS inhibitor pipelines to the installation of disconnecting devices in front of RC;
- periodic supply of glycols (diethylene glycol) using pumps with GGS inhibitor pipelines to the wellhead and the flowline;
- a method of pressure reduction (blowing a well, a flowline, a gas-gathering manifold);
- heating of the place of hydrate formation of the ground section at the GGS using hot water;
- heating of the place of hydrothermal formation with the help of steam from a mobile steam unit (MSU).

The application of the above methods depends on the individual UGS technological scheme. More often, hydrate formation is observed at the disconnect device assembly before the RC, and to prevent it, the installation of electric heating cables is an effective measure.

The above methods for preventing and eliminating hydrate formation are, of course, costly measures and can have negative economic, technological and environmental consequences. In this regard, it is necessary to approach the solution of this problematic issue carefully and develop effective measures.

The authors proposed to implement an integrated approach to ensuring control over the operation of wells and a gas gathering station, which includes:

- to perform automatic monitoring of gas storage wells operation parameters. Therefore, for operational control of well operation parameters (pressure and temperature) at the disconnecting devices and GGS installation, it is advisable to install pressure and temperature sensors with the output of operating parameters to the automated workstation (AWS) of the operator and geologist. This will make it possible to track changes in thermobaric parameters and take timely measures to prevent hydrate formation;
- based on the actual pressure and temperature data, build the dependence of the change in parameters along the length of the flowline with an interval (200 ... 500 m) with the stable well operation. In case of a decrease in pressure and temperature parameters, establish the probable causes of these complications. Based on the results of industrial research, establish the optimal parameters for well operation;
- to establish the possible places of the most frequent deposition of hydrates on wells and technological equipment of the gas storage;
- to consider the possibility of installing electronic pressure gauges to control pressure and temperature along the gas flow path from the wellhead to the gas gathering station;
- to control the hydraulic condition of the wells and the flowlines according to the actual values (pressure, temperature, productivity) and by performing calculations of pressure losses along the length. To prevent the accumulation of liquid contaminants in the well and the internal cavity of the flowlines, remove it periodically by creating a high-speed gas flow, as well as using various methods [11-14];
- to create a software program to control the main parameters of gas storage operation (gas flow rate, hydraulic resistance, hydraulic efficiency, etc.);
- for each gas storage, select the best methods for preventing and eliminating hydrate formation based on technical and economic calculations.

These days, gas storage facilities play an important role, since the required volume of gas is supplied on time and thereby the pressure balance in the GTS gas pipeline system is ensured. For the effective management of the gas storage facility, it is advisable to develop new software that will allow in the shortest possible time to predict the main parameters of operation under different conditions. In addition, it is important to ensure the stable operation of the gas storage facility under various complicating factors. Considering this, in the future, it will be relevant to create software that allows real-time monitoring of well operation and identification of complicating factors when certain prerequisites arise.

Thus, when implementing the program in practice, specialists can easily and quickly calculate various hydrate-free modes of UGS operation. Based on the results of the calculations, it is possible to determine the optimal mode of operation of the UGS facility.

When operating wells with high productivity and high reservoir pressure, considering the gas flow passes through the control nozzles, a sharp drop in temperature occurs, as a result of which freezing of pipelines and process equipment can be observed (Fig. 2). Such a sharp decrease in temperature causes the process of hydrate deposition.

Fig. 2. General view of the piping at the gas pipeline inlet of the installation of disconnecting devices at the gas gathering station

The fitting is adjusted by changing the gate cross-sectional area of the opening of the adjusting valve (increases or decreases). A general view of the fitting of the regulating choke and regulating units with different opening degrees is shown in Figure 3 [15].

In Figure 4 a diagram of the regulating choke set RC-12 is shown, which is mounted on the inlet gas pipeline of the installation of disconnecting devices at the main gas gathering station.

Fig. 3. Regulating choke and regulating units

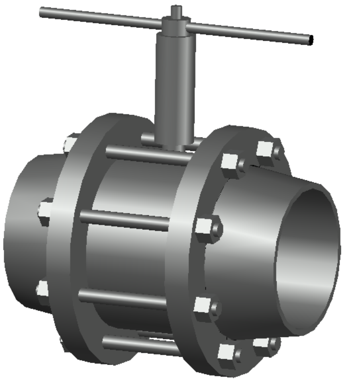

Fig. 4. The regulating choke set RC-12 layout

4. Results and discussion

Experimental studies of hydrate formation processes at the installation site of regulating chokes under real operating conditions of gas pipelines are difficult to perform due to a large number of problems, in particular, high pressure. Therefore, to determine the zones prone to hydrate formation during the passage of the gas flow through the regulating chokes, CFD modeling was performed, which is an effective tool for studying the characteristics of multiphase flows in various elements of gas pipeline systems, in particular, fittings (branches, tees) [16]. CFD modeling allows seeing in detail the three-dimensional multi-phase flow in various elements of the pipeline and studying pressure losses, phase distribution (volume fractions), flow velocities, turbulence, kinetic energy, etc.

For CFD modeling of hydrate formation processes at the installation site of control nozzles, the ANSYS Academic 2021 R2 finite element analysis software package, namely the ANSYS Fluent computational fluid dynamics (CFD) code, was chosen.

To study complex multi-phase flow in regulating chokes, the best approach for applying is the Euler approach, namely the Mixture model – a model of a multi-phase mixture. The Mixture model applies to two or more phases. This model allows mutual penetration into phases. Therefore, for multiphase flows, the concept of the volume fraction phase is introduced, which is another additional flow parameter. Bulk particles of the continuous phase q and the dispersed phase p can have any value from 0 to 1, depending on how much space they occupy. The Mixture model allows the phases to move at different speeds. In the Mixture model, only one of the phases can be compressed.

The Mixture model incorporates the continuity equation for the mixture, the conservation of momentum and energy balance of the mixture, the volumetric particle equation for dispersed phases, and algebraic expressions for relative velocities (if the phases move at different velocities). These equations are discussed below.

Mixture continuity equation

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \bar{v}_m) = 0, \tag{2}$$

where
ρ_m – relative mixture density;
$\bar{v}_m$ – relative mixture velocity.

The momentum equations of the mixture can be obtained by adding separate momentum equations for each phase

$$\frac{\partial}{\partial t}(\rho_m \bar{v}_m) + \nabla \cdot (\rho_m \bar{v}_m \bar{v}_m) = -\nabla p + \nabla \cdot \left(\mu_m (\nabla \bar{v}_m + \nabla \bar{v}_m^T)\right) + \rho_m \bar{g} + \bar{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \bar{v}_{dr,k} \bar{v}_{dr,k}\right), \tag{3}$$

where
$\bar{F}$ – bode force;
μ_m – mixture viscosity;
$\vec{g}$ – gravity acceleration;
$\bar{v}_{dr,k}$ – drift rate of the dispersed phase k.

The relative velocity (also called the sliding velocity) is the difference between the velocity of the dispersed phase p and the velocity of the continuous phase q

$$\bar{v}_{pq} = \bar{v}_p - \bar{v}_q, \tag{4}$$

where
$\bar{v}_p$ – dispersed phase velocity;
$\bar{v}_q$ – continuous phase velocity.

The drift velocity of the dispersed phase is the difference between the slip rate and the algebraic sum of the products of mass particles by the velocity of the dispersed phase

$$\bar{v}_{dr,p} = \bar{v}_{pq} - \sum_{k=1}^{n} c_k \bar{v}_{pk}. \tag{5}$$

Equation of the mixture energy balance

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k h_k) + \nabla\cdot\sum_{k=1}^{n}\left(\alpha_k\bar{v}_k(\rho_k h_k + p)\right) = \\ = \nabla\cdot\left(k_{eff}\nabla T\right) + S_E, \quad (6)$$

where

k_{eff} – efficient conductivity;

h_k – phase $k$enthalpy;

S_E – conductive energy transfer. S_E includes any other bulk heat source.

From the equation of dispersed phase p continuity the equation of volume fraction for the dispersed phase p can be obtained

$$\frac{\partial}{\partial t}(\alpha_p\rho_p) + \nabla\cdot(\alpha_p\rho_p\bar{v}_m) = -\nabla\cdot(\alpha_p\rho_p\bar{v}_{dr,p}). \quad [17]\ (7)$$

CFD modeling was performed by numerically solving the indicated equations, closed by a two-parameter turbulence model using a near-wall function with appropriate initial and limit conditions.

A 3D geometric model of the regulating choke RC-12 was built (Fig. 5). The opening of the regulating choke unit is 50 mm, the outer diameter of the sections of the pipeline adjacent to it is 133 mm, the nominal wall thickness is 6 mm, the inner diameter of the adjacent sections of the pipeline is 121 mm. To study the dynamics of the gas flow movement by the regulating choke, a 3D geometric model of its internal cavity, along which the flow moves, was built. The geometric model of the internal cavity of a fully open regulating choke with adjacent sections of the pipeline is shown in Figure 5.

Gas-dynamic processes along with the regulating choke, which affects the location of potential zones prone to hydrate formation and the intensity of hydrate formation, significantly depend on the degree of opening of the choke. Therefore, three-dimensional geometric models of the regulating choke were drawn with varying degrees of its opening. The opening rates were 100%, 75%, 50%, and 25%. Such modeling was performed by changing the cross-sectional area of the choke control opening. Under the operating conditions of gas pipelines, such a change is made by lowering the gate. For each stage of the opening of the regulating choke, a separate simulation was performed and the influence of this parameter on the location of potential zones prone to hydrate formation and the intensity of hydrate formation was investigated.

The following limiting conditions are given for research (Fig. 5). At the inlet to the control section of the pipeline adjacent to the regulating choke, the medium was set. The first phase of the medium was natural gas. Natural gas was taken as a compressible medium. It seemed that the density of natural gas depends on the parameters of the flow (in this case, the energy equation is automatically added to the equations being solved). The second phase of the medium was set to the liquid phase – water drops. The specified volume fraction of the liquid phase at the inlet was 0.2. Also, at the inlet, the flow velocity was set, taken equal to 1.8 m/s, corresponding to the operational parameters.

At the pipeline section outlet adjacent to the regulating choke, the pressure equal to 5.3 MPa was set.

At the inlet, the temperature of the medium was set to 280 K, and at the outlet, 268 K, which corresponds to the operational parameters. Also, at the inlet and outlet, the turbulence intensity to 5% (for this value, the flow is considered to be completely turbulent), and the hydraulic diameter was set. The hydraulic diameter was assumed to be equal to the inner diameter of the control sections of the pipeline adjacent to the regulating choke. It was found that the force of gravity acts on the gas flow.

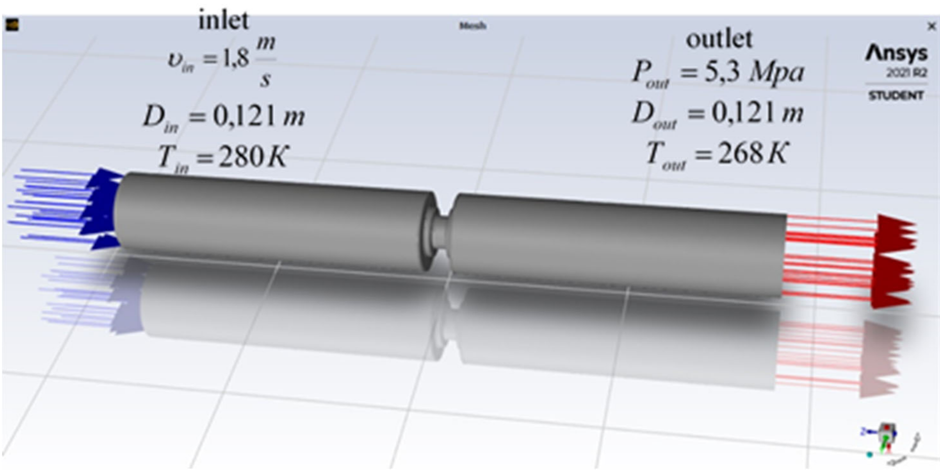

Fig. 5. Regulating choke design model

The main parameters of the model are presented in Table 1.

Table 1.
Basic model parameters

Indicator	Value
Diameter of an opening of a regulating body of the union, mm	50
Pipeline internal diameter, mm	121
Inlet flow rate, m/s	1.8
Outlet pressure, MPa	5.3
Inlet temperature, K	280
Output temperature, K	268
Volumetric fraction of liquid phase at the inlet	0.2
Intensity of turbulence at the input, %	5
Intensity of turbulence at the output, %	5

The results of the CFD simulation were visualized in the post-processor of the ANSYS Fluent software package, which made it possible to see the flow structure in the element under study for different degrees of opening of the regulating choke. The distribution of the volumetric part of natural gas (Fig. 6) and water (Fig. 7) in the internal cavity of the element under study was constructed for different degrees of opening of the regulating choke. Also, the simulation results were visualized by constructing flow lines, which were colored in the color of the gas flow velocity (Fig. 8). The influence of the degree of opening of the regulating choke on the location of potential zones prone to hydrate formation was evaluated. Numerical results (Figs. 6, 7) show that after the passage of the gas flow through the regulating choke, an uneven redistribution of bulk phase particles occurs. With a fully open regulating choke (100%), the maximum values of the volume fraction of the liquid phase are concentrated at the beginning of the pipe adjacent to the regulating choke, in the direction of flow, near the wall along the entire circle of the pipe (Fig. 6a). The reverse picture is observed with the volume fraction of natural gas (Fig. 7a). In these places, the volume fraction of natural gas is the smallest. Such a redistribution of bulk phase particles is due to the dynamics of the flow through the regulating choke. With a fully open regulating choke, the regulating flow through the opening of its regulating body is significantly accelerated, and at the beginning of the pipe adjacent to the regulating choke, a high-velocity flow is formed with a diameter approximately equal to the diameter of the opening (Fig. 8a). Since the diameter of the pipe adjacent to the regulating choke is larger than the diameter of the opening of its regulating body, a stagnant zone is

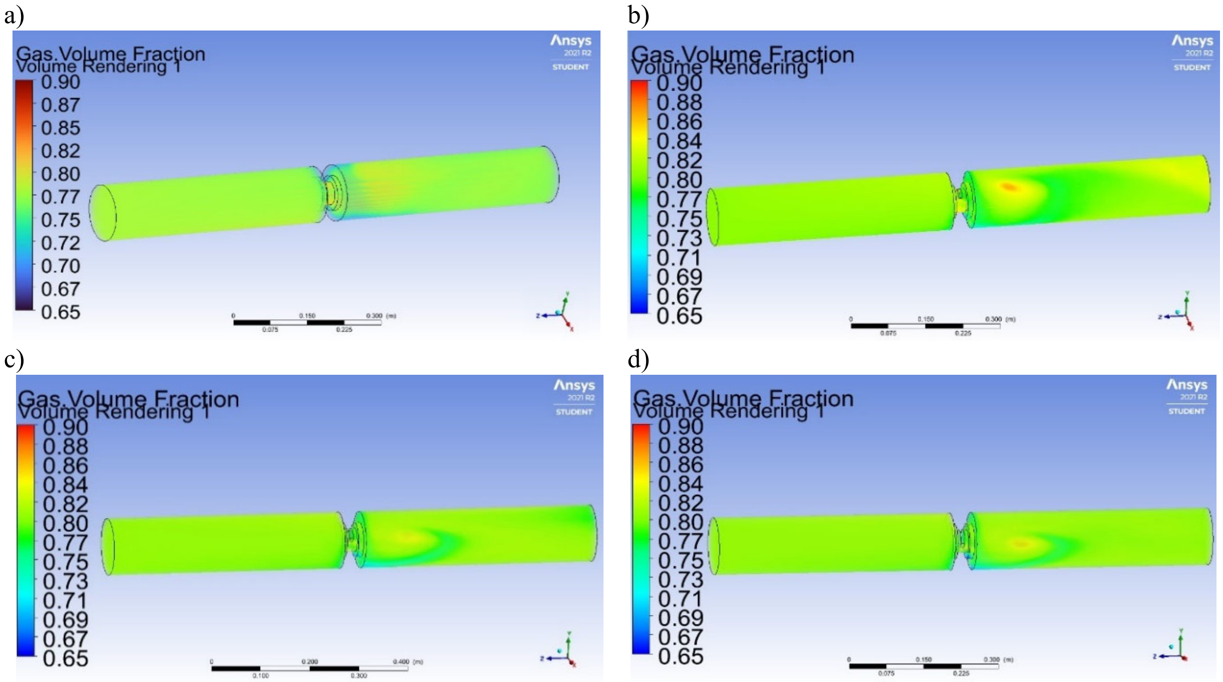

Fig. 6. Distribution of the water volume fraction in the inner cavity of the test element for different opening degrees of regulating choke: a) opening degree 100%; b) opening degree 75%; c) opening degree 50%; d) opening degree 25%

formed in the annular space between the pipe wall and the high-velocity flow, where the liquid phase accumulates and therefore its volume fraction is maximum here. Under favorable conditions (pressure, temperature), hydrates start to form in this zone, the amount of which will increase with time. If, however, the damper of the adjusting body of the regulating choke to lower the high-velocity flow becomes shorter and more and more displaced to the lower part of the pipe adjacent to the regulating choke (Figs. 8a,b,c), as a result of which a large zone of swirling flow is formed in the upper part of the pipe and then there are no maximum values of the bulk particle of the liquid phase in this place (Figs. 6b,c,d), in contrast to the case when the regulating choke is fully open (Fig. 6a). In the case of lowering the gate of the adjusting body of the regulating choke, the maximum values of the volumetric part of the liquid phase are concentrated under the high-velocity flow at the beginning of the pipeline section adjacent to the regulating choke (in its lower part). Moreover, the more the gate is lowered, the greater the volume fraction of the liquid phase is in this place (Figs. 6b,c,d). Therefore, if the regulating choke is not fully opened in case of favorable conditions, hydrates will start to form only in the lower part of the pipe adjacent to the regulating choke at its inlet. So, when the regulating choke is fully opened, the zone of hydrate formation is the largest.

Partial overlap of the regulating choke leads to a significant reduction in the zone of hydrate formation. Therefore, under favorable conditions for the formation of hydrates, namely in the cold season, it is recommended to perform a partial overlap of the adjusting fitting periodically, which will lead to the removal of most of the liquid phase from the places of its accumulation.

<u>Development of measures and methods for monitoring the process of hydrates formation at gas storage facilities</u>

During the period of gas withdrawal from the productive horizon of the UGS, wet saturated gas in the wells through the column of lift pipes enters the surface, and then by a flowline (gas pipeline), which can have upstream, downstream, and straight sections, various local supports, enters the GGS, where mechanical purification out of impurities and liquids takes place. Next, the gas enters the drying unit, if necessary, it is compressed and metered before entering the main gas pipeline. The deposition of hydrates can only occur in the presence of liquid in the flow and a certain range of pressures and temperatures. When gas flows into the gas storage communications, its pressure and temperature are constantly changing, therefore, favorable conditions for the formation of hydrates arise in different periods of operation in different areas of gas flow.

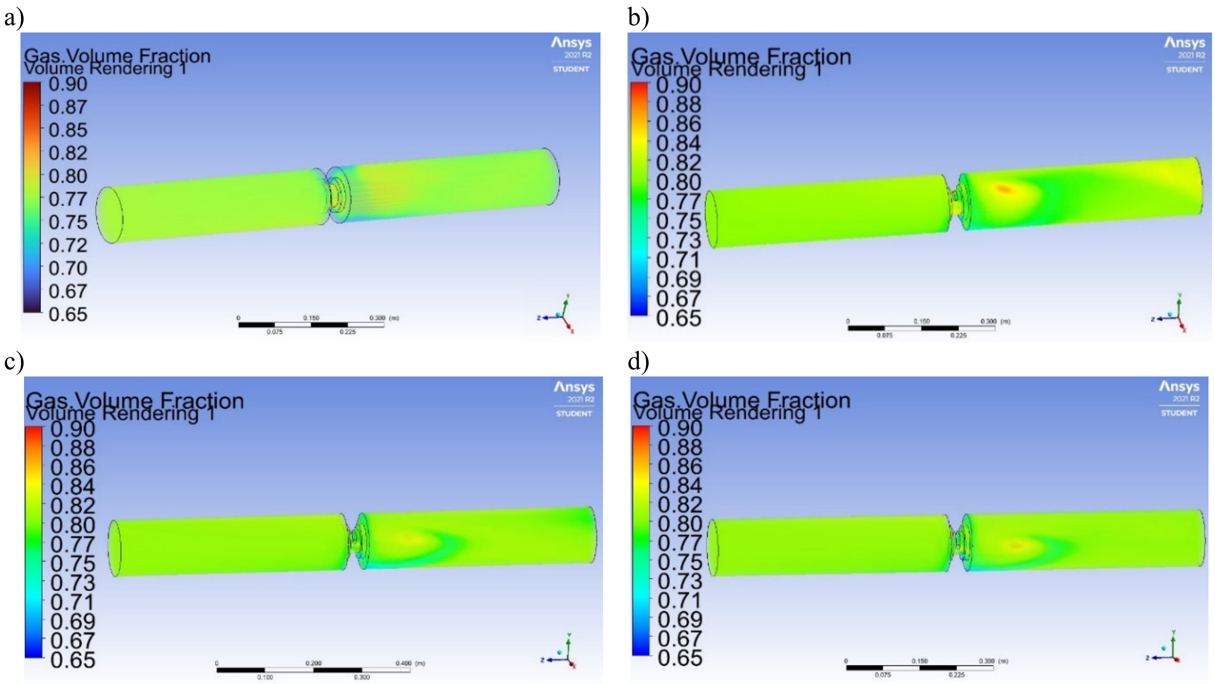

Fig. 7. Distribution of the natural gas volume fraction in the inner cavity of the test element for different opening degrees of regulating choke: a) opening degree 100%; b) opening degree 75%; c) opening degree 50%; d) opening degree 25%

Without a mathematical model for the operation of UGS industrial equipment and its constant updating with the current values of thermobaric parameters, it is difficult to control and predict the formation of hydrates.

For statistical analysis of the probability of hydrate formation in different units of the gas storage network, the processing of actual industrial data on the operation of wells and gas pipelines was carried out. It has been established that

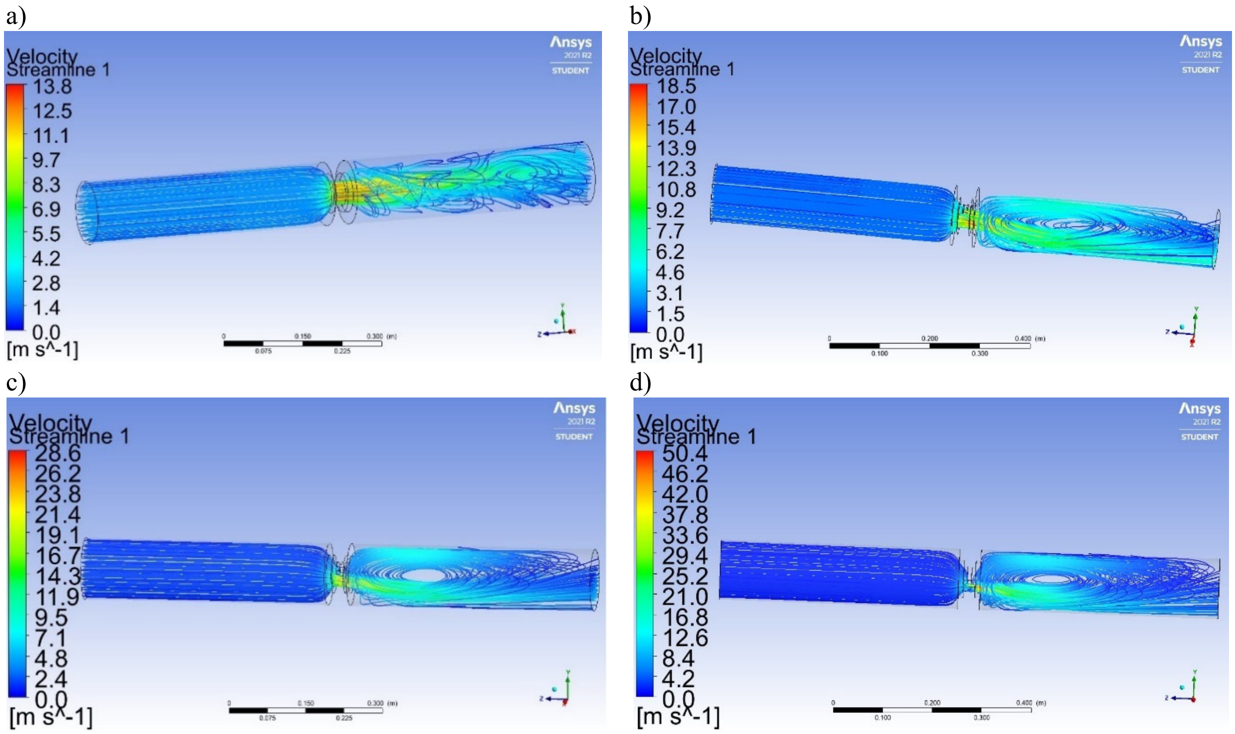

Fig. 8. The flow lines are in the colors of the gas flow rate in the inner cavity of the test element for different opening degrees of regulating choke: a) opening degree 100%; b) opening degree 75%; c) opening degree 50%; d) opening degree 25%

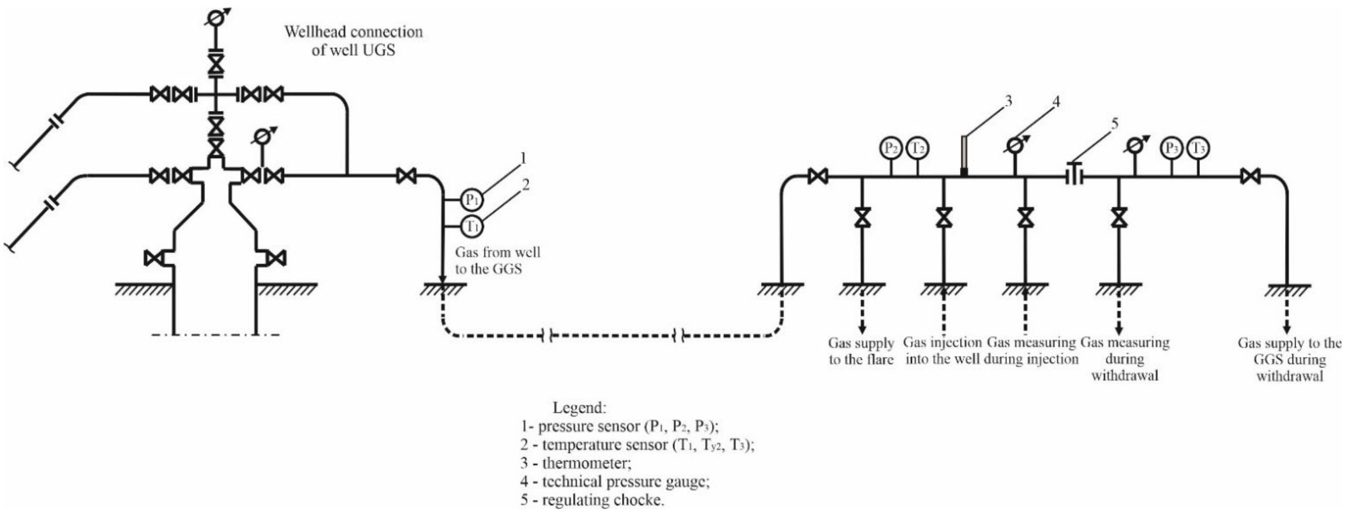

Fig. 9. Schematic diagram of installation of pressure and temperature sensors at the wellhead and at the installation of GGS disconnecting devices

the largest pressure drop during gas extraction from underground storage facilities is achieved at the GGS control valves with a significant excess of reservoir pressure over the pressure in the main gas pipeline. During gas storage facilities operation with high productivity and high reservoir pressure, the formation of hydrates, first of all, occurs on the regulating chokes, which are used to set the desired well productivity. Also, the formation of hydrates in the X-mas trees of wells and their flowlines is observed at UGS facilities.

Taking into account the most probable zones of hydrate formation in underground storage facilities and to ensure high-quality control of changes in thermobaric parameters during gas flow, a layout of measuring instruments (pressure and temperature gauges) (Fig. 9) and an algorithm for their interrogation and analysis of the possibility of hydrate formation in the current wells operating mode (Fig. 10) were proposed. According to the proposed scheme, it is envisaged to install pressure and temperature sensors on the flowline directly at the outlet of the well's X-mas tree and the GGS

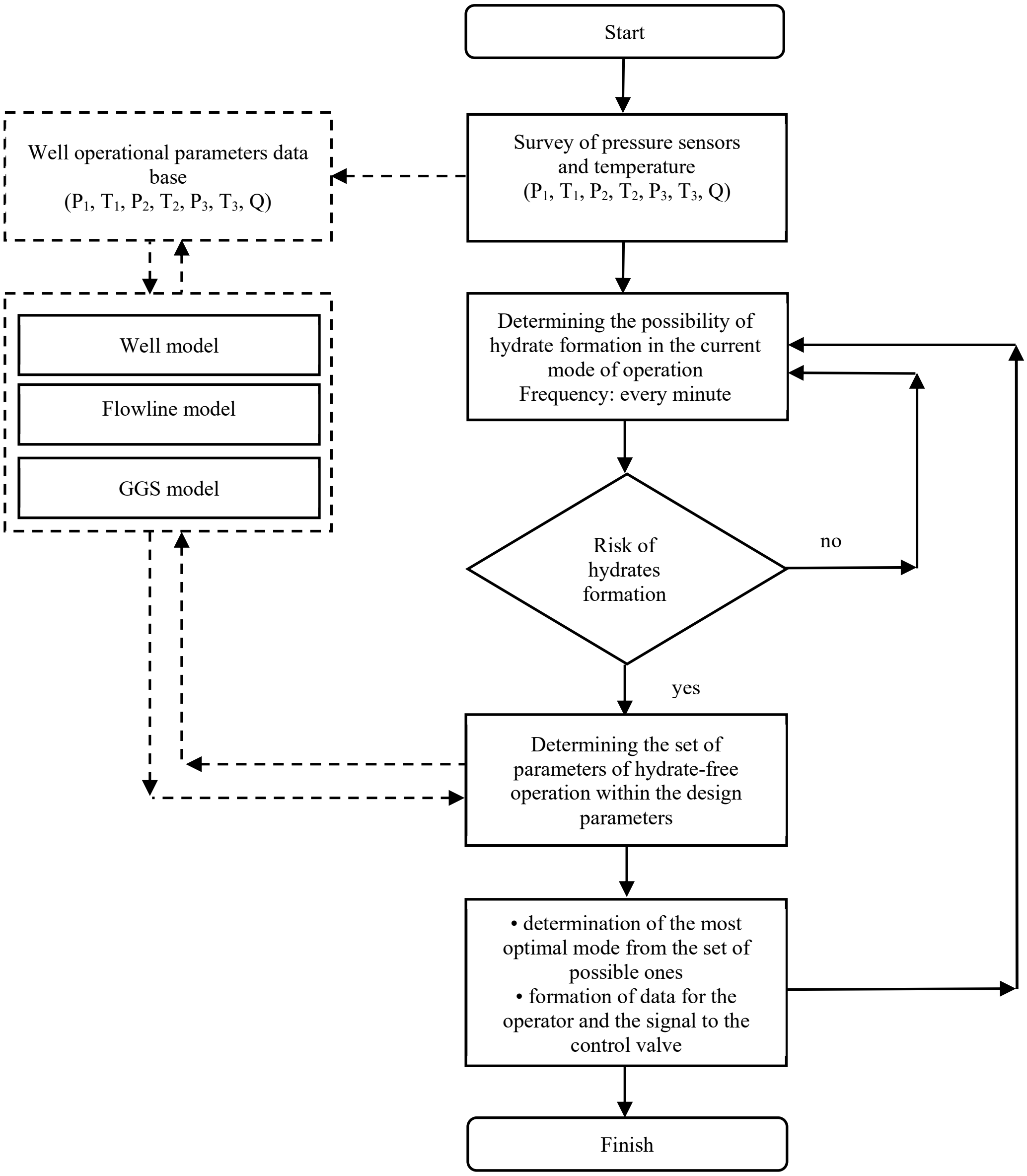

Fig. 10. Algorithm for controlling the current mode of wells operation

before and after the regulating choke. In practice, it is also necessary to take into account the individual profile of gas pipelines and the presence of branches, and, if necessary, provide additional places for monitoring pressure and temperature. Analyzing the design documentation of technological facilities and gas storage networks, it is possible to predict the zones of the most probable accumulation of liquid and hydrates formation.

When withdrawing gas to a gas storage facility, a different number of wells may be in operation which depends on the current mode of the gas storage facility operation. It is also possible to ensure the required performance of the gas storage facility using chokes installed to regulate the individual well regime. Working pressures and flow rates of individual wells can vary significantly, due to the uneven reservoir properties of the formation, well design, and the given regime. All these factors determine the multi-variant mode of operation of the elements of the gas-dynamic system "well - flowline - gas gathering station" to ensure the required performance of the gas storage facility. The required capacity of the gas storage facility can be achieved under various modes of operation of individual wells, however, not all modes of wells operation is stable and may be accompanied by hydrate formation. The stock of production and injection wells at individual gas storage facilities in Ukraine ranges from 50 to 350 units. With such a quantity of wells, an operational qualitative analysis of the operation mode of the gas gathering network is possible only with the use of electronic computing technology. Automated analysis of all possible modes for individual elements of the gas gathering network for a given total capacity of the gas storage facility allows choosing the most optimal one from the set of acceptable modes, which will provide the lowest probability of hydrate formation. In Figure 10 an algorithm for monitoring the current mode of well operation was proposed, which involves analyzing pressure and temperature indicators to assess the possibility of hydrate formation in the current mode and determining the optimal scheme of well operation modes, and developing and taking measures to prevent hydrate formation.

It should be noted that hydrates accumulation is a process that is difficult to predict and can last both a short period and a long one. If hydrates start to be accumulated with low intensity, then it is difficult to detect them, and only a sufficiently significant decrease in the pressure of the gas flow on the GGS will indicate the occurrence of complications. Untimely adoption of measures to prevent hydrates formation can lead to the cessation of gas flow from the well and its emergency shutdown.

The authors analyzed in detail the problem of hydrates formation in UGS facilities and proposed to use an intelligent system for monitoring and regulating the operation of the wells to solve it. It is envisaged that such a control system should contain:

- pressure and temperature sensors at the wellhead and GGS;
- controller with software including algorithms for polling sensors, analysis of current operating parameters, and generation of commands to operate the control valves;
- a server for archiving data of well operation parameters;
- operator's workstation for monitoring the current parameters of wells' operation and displaying notifications about possible complications.

5. Conclusions

To ensure the reliable operation of gas storage facilities in the conditions of hydrate accumulation, it is advisable to take comprehensive measures to prevent their formation, through the implementation of modern intelligent control and process management systems. The proposed complex measures include control of well operation parameters at the installation of disconnecting devices with the output of the pressure and temperature values of the working parameters on the workstation; selection of the optimal mode of wells and flowlines operation to prevent complications; automated data processing, signaling the possibility of hydrate formation and the need for inhibitors or other measures. Automation of the operating parameters control obtained at the gas gathering system of the gas storage facility allows not only to control the conditions of hydrate formation but also to determine the optimal modes of wells' operation.

It is shown that CFD modeling is an effective tool for gaining an understanding of the complex physical processes that occur during the movement of multiphase flows through gas pipeline systems. Based on the results of CFD modeling, it was found that the position of the regulating choke at underground gas storages depends on the distribution of phases at the inlet of the pipe adjacent to the choke, and hence the location of the zones of hydrate formation. The simulation results showed that with a fully open regulating choke, a potentially favorable place for hydrate formation is the inlet of the pipe adjacent to the choke, in the direction of flow, near the wall along the entire circle of the pipe. This is the zone where the greatest accumulation of the liquid phase of the gas flow occurs in this case. If the regulating choke is not fully open, then a potentially favorable place for the formation of hydrate is the lower part of the pipe adjacent to the regulating choke at its inlet. Such results were substantiated by a detailed analysis of gas-dynamic processes at the place of installation of the regulating choke, determination of the zones of water accumulation in the internal cavity of the gas pipeline. The obtained results can help to provide zones of hydrate accumulation in the places of installation of regulating choke and prevent their formation and blocking of the flow by periodically partially blocking the regulating choke.

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