DOI: 10.5604/01.3001.0053.5955

Volume 117 • Issue 1 • March 2023

Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Development of methods for predicting hydrate formation in gas storage facilities and measures for their prevention and elimination

V.B. Volovetskyi [a,*], Ya.V. Doroshenko [b], S.V. Matkivskyi [c], P.M. Raiter [d], O.M. Shchyrba [e], S.M. Stetsiuk [e], H.Ya. Protsiuk [f]

[a] Branch R&D Institute of Gas Transportation Joint Stock Company "Ukrtransgaz", 16 Koneva str., Kharkiv, Ukraine

[b] Department of Oil and Gas Pipelines and Storage Facilities, Institute of Petroleum Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska str., Ivano-Frankivsk, Ukraine

[c] Joint Stock Company "Ukrgasvydobuvannya", 26/28 Kudriavska str., Kyiv, Ukraine

[d] Department of Energy Management and Technical Diagnostics, Institute of Architecture, Construction and Power Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska str., Ivano-Frankivsk, Ukraine

[e] Branch Ukrainian Scientific Research Institute of Natural Gases Joint Stock Company "Ukrgasvydobuvannya", 20 Himnaziina Naberezhna str., Kharkiv, Ukraine

[f] Department of Applied Mathematics, Institute of Information Technologies, Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska str., Ivano-Frankivsk, Ukraine

* Corresponding e-mail address: vvb11@ukr.net

ORCID identifier: https://orcid.org/0000-0001-8575-5143 (V.B.V.)

ABSTRACT

Purpose: The purpose of this work is to study the processes of hydrate formation during the operation of wells and underground gas storage facilities. Development of a set of measures aimed at the prediction and timely prevention of hydrate formation in wells and technological equipment of gas storage facilities under different geological and technological conditions.

Design/methodology/approach: The prediction of hydrate formation processes was carried out using a neural network that is a software product with weight factors calculated in MATLAB environment and the ability to adapt parameters of the network specified to updated and supplemented input data during its operation. So, within the MATLAB software environment, a software module of a two-layer artificial neural network with a random set of weight factors is created at the first stage. In the second stage, the neural network is trained using experimental field input/output data set, output data. In the third stage, an artificial neural network is used as a means of predicting hydrate formation with the ability to refine weight factors during its operation subject to obtaining additional updated data, as an input set, for modifying the coefficients and, accordingly, improving the algorithm for predicting of an artificial neural network. In the absence of new data for the additional training of an artificial neural network, it is used as a computing tool that, on the basis of input data about the current above-mentioned selected technological parameters of fluid in the pipeline, ensures the output values in the range from 0 to 1 (or from 0 to 100%), that indicates the probability of hydrates formation in the controlled section of the pipeline. Application of such an approach makes it possible to teach; additionally that is, to improve the neural network; therefore this means of predicting hydrate formations objectively increases reliability of results obtained in the process of predicting and functioning of the system.

The authors of the work recommend to carry out an integrated approach to ensure clear control over the operation mode of wells and gas collection points.

Findings: According to the results of experimental studies, the places of the most likely deposition of hydrates in underground gas storage facilities were identified, in particular, in the inside space of the flowline in places of accumulation of liquid contaminants (lowered pipeline sections) and an adjustable choke of the gas collection point. The available methods used to prevent and eliminate hydrate formation both in wells and at gas field equipment were analyzed. Such an analysis made it possible to put together a list of methods that are most appropriate for the conditions of gas storage facilities in Ukraine.

The method of predicting hydrate formation in certain sections of pipelines based on algorithms of artificial neural networks is proposed. The developed methodology based on data on values of temperatures and pressures in certain sections of pipelines allows us to predict the beginning of the hydrate formation process at certain points with high accuracy and take appropriate measures.

Research limitations/implications: To increase the efficiency of solving the problem of hydrate formation in gas storage facilities, it is expedient to introduce new approaches to timely predict complications, in particular, the use of neural networks and diverse measures.

Practical implications: Implementation of the developed predicting methodology and methods and measures to prevent and eliminate hydrate formation in wells and technological equipment in underground gas storage facilities will increase the operation efficiency of underground gas storage facilities.

Originality/value: The use of artificial intelligence to predict hydrate formations in flowlines of wells and technological equipment of underground gas storage facilities is proposed. Using this approach to predict and functionthe system as a whole ensures high reliability of the results obtained due to adaptation of the system to the specified control conditions.

Keywords: Well, Flowline, Hydrates formation, Adjusting choke, Technological equipment, Neural network

Reference to this paper should be given in the following way:

V.B. Volovetskyi, Ya.V. Doroshenko, S.V. Matkivskyi, P.M. Raiter, O.M. Shchyrba, S.M. Stetsiuk, H.Ya. Protsiuk, Development of methods for predicting hydrate formation in gas storage facilities and measures for their prevention and elimination, Journal of Achievements in Materials and Manufacturing Engineering 117/1 (2023) 25-41. DOI: https://doi.org/10.5604/01.3001.0053.5955

ANALYSIS AND MODELLING

1. Introduction

The main purpose of underground gas storage (UGS) facilities is to ensure reliable gas supplies to consumers, including covering seasonal fluctuations in its consumption, ensuring stable export and transit supplies, improving the reliability of main gas pipelines operation, and strategic reservation of reserves in case of emergencies. Of course, gas storage facilities play an important role in ensuring the stable operation of the gas transmission system of Ukraine, which requires increased attention towards identifying and preventing possible complications in their functioning.

During the operation of gas storage facilities, many problematic issues arise that need to be addressed immediately. In this regard, in order to ensure the stable operation of gas storage facilities, a detailed analysis of all technological processes is carried out, possible complications are identified, and measures are developed to prevent and eliminate them.

Thus, possible complications at UGS facilities include the problem, particularly the presence of moisture in gas flow. Within reservoir conditions, natural gas is in contact with water and is saturated with its vapours. Because of this, hydrates can be formed during the operation of wells when thermodynamic conditions change along the path of gas movement from the reservoir to the gas collection point (GCP). From practical experience, it is known that hydrates can be deposited in the inner annulus of tubing from the bottomhole to the wellhead and then in the tie-in of Xmas tree of the well (valves, spools, T-joints), in flowline, both in straight-line sections and in local supports (lowered sections, outputs, crossovers, tees, welding joints, etc.), in surface and underground pipelines of the gas collection point, shutdown valves, plug valves, valves, chokes, collectors, technological equipment, etc. Besides that, hydrates are often observed after an adjustable choke, with the help of which the mode of the well operation is regulated.

Hydrate formation leads to a decrease in the drift diameter of the inside space of the pipeline and, accordingly, to a decrease in the rate of wells. In some cases, their operation can be suspended. This negatively affects the possibility of ensuring the technological mode of wells and achieving the required productivity of gas storage facility for the further supply of planned volume of gas to the commercial gas pipeline. Therefore, this problem needs to be analyzed in detail, new effective approaches to its solution need to be proposed, and a number of measures to prevent hydrate formation using modern technological advances need to be developed.

2. Literature review

Ukraine is one of those countries that satisfy only a small part of the demand for fuel and energy resources on account of its own production, which indicates a significant dependence on imported energy reserves supply. Consumption of gas and petroleum products is relatively stable while the level of production decreases smoothly every year [1,2]. The reason for this is a significant depletion of the main hydrocarbon deposits and their natural transition to the final stage of development [3,4].

The complexity of the production of residual hydrocarbon reserves at the final stage is associated with low reservoir pressures, the intensive flow of edgewater and bottom waters into deposits, flooding of the existing wells fund, corrosion and erosion of surface and downhole equipment, etc. [5-7].

Natural gas produced within such conditions is sufficiently humid (moisture content 750-1000 g/m^3). The presence of water, water vapour in production under certain thermobaric conditions lead to hydrate formation in the system, that can cause an emergency situation due to the formation of hydrate corks.

The problem of hydrate formation arose with the development of gas industry in the world, in particular, the introduction of the first gas fields into commercial development. In 1934 the American scientist, E.G. Hammerschmidt, studied hydrate formation [8]. The scientist found out that gas hydrates can form and accumulate in gas pipelines, causing their plugging. The scientist also proposed to use of inhibitors to combat hydrates. According to the results of the analysis of experimental data obtained for various inhibitors, E.G. Hammerschmidt proposed an empirical formula for assessing their effectiveness [9]:

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

where

ΔT – decrease in hydrate formation temperature;

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

X – concentration of inhibitor, % (w);

M – molecular weight of inhibitor.

American researchers Deaton and Frost made a significant contribution to the study of gas hydrates. These researchers published a monograph on the problem of preventing hydrate formation in gas pipelines that provides experimental data on phase equilibriums of gas hydrates of hydrocarbon gases [10]. The study of the problem of gas hydrates was also carried out by many other researchers, who conducted a significant number of both theoretical and experimental studies that made it possible to obtain certain knowledge to combat this complication [11].

The rapid development of the gas industry necessitated the generalization of conducted studies on the problem of hydrate formation in order to develop measures to prevent their formation and accumulation in gas pipelines during gas production and transportation to consumers. According to the results of industrial research, effective methods were determined to combat hydrate formation while producing and transporting natural gas [12].

In the 1970s of the last century, many different methods were used in gas fields to prevent and eliminate hydrate formation [13]. Thus, to prevent hydrate formation in wells and gas collection systems, the following methods were known:

- heating of components and sections to increase the gas temperature above the equilibrium temperature of possible hydrate formation;
- injection of inhibitors into the gas flow;
- elimination of sudden pressure drops that contribute to lowering the gas temperature and formation of hydrates in fittings, etc.;
- reduction of pressure in the collection system below the equilibrium pressure of hydrate formation;
- reduction of turbulence degree of the gas flow in order to reduce the intensity of gas and liquid mixing;

- systematic removal of fluid that accumulates in low places of the collection system.

Besides that, methods were also developed to eliminate hydrate formation that is similar by principle to the methods of prevention but is characterized by a range of differences.

To eliminate hydrate formation in wells, the following methods were known: blowing into the atmosphere; circulation of the inhibitor through siphon pipes that are lowered into the well; flushing with hot brine under pressure; and gas collection systems – heating the places of hydrate formation or supplying a hot agent directly to the hydrate cork; use of an inhibitor; a sharp pressure drop (blowing into the atmosphere); reducing the pressure from both sides of a hydrate cork, followed by blowing into the atmosphere; cessation of gas supply for a certain period, sufficient for the decomposition of hydrates with the heat of the surrounding soil, followed by blowing into the atmosphere.

In the works [14,15], the main inhibitors that are used in the gas industry are provided, that include methyl alcohol (methanol), calcium chloride, and glycols (ethylene glycol, diethylene glycol, triethylene glycol). The main criteria when choosing an inhibitor are the property of reducing the equilibrium temperature of hydrate formation, cost, solubility in water, the freezing point of water solutions, viscosity, surface tension, etc. The consumption of the inhibitor depends on gas content in formation and wellhead conditions, the rate of the well, temperature and pressure, the component composition of gas and hydrocarbon presence, flowline properties, etc.

In [16], it is proposed to use a complex inhibitor against hydrate formation, and corrosion OV-07 that prevent hydrates deposition and corrosion of equipment in wells.

[17] have developed a new model of the interfacial interactions between a hydrated particle and a solid surface and between a hydrated particle and a hydrated surface. This model, for the first time, accounts for the premelting behaviour of hydrate surfaces. Showed that the adhesive forces between the hydrate particles and the pipe wall increase strongly when the surface of the pipe is more hydrophilic.

At present, the problem of hydrate formation is topical and requires detailed study and development of new effective methods to prevent this phenomenon.

3. Methods and materials

During gas withdrawal from UGS facilities, thermobaric conditions change along the path of gas movement from the reservoir to the place of transmission to the commercial gas pipeline. At the same time, gas with liquid and mechanical solids from wells enters the gas collection point, where it is cleaned, dehydrated, metered and compressed, from where it is supplied into the main gas pipeline to consumers.

Hydrate formation can occur in different sections, in particular, while the movement of gas in the perforation interval, in the wellbore, on the wellhead, in the flowline, etc. During the operation of a well, when gas moves from the formation to the bottom hole, it is throttled in the perforation interval, which leads to a decrease in its temperature. The decrease of temperature depends on filtration properties of the bottomhole zone of the formation, perforation, rate and thermobaric conditions. In case of contamination or an insufficient number of perforation holes of production casing and high rates of wells, a sharp decrease in temperature of gas flow and hydrate formation is possible. Besides the decrease in temperature, conditions of hydrate formation are also affected by a change in pressure.

Also, a decrease in gas temperature occurs along the wellbore that is influenced by many factors: gas throttling due to the presence of contaminants in the tubing, heat exchange with surrounding rocks, the friction of gas by the wall of tubing pipes, etc.

During gas movement on the wellhead (Xmas tree and tie-in), the most likely places of hydrate formation are in valves, outputs, T-joints, spools, crossovers, rock catchers, thermal pockets, and samplers. On surface sections of pipelines, hydrate formation is controlled by installing pressure and temperature sensors that record the corresponding values.

Also, gas transportation by flowlines from the wellhead to the gas collection point can be complicated by the deposition of hydrates in internal space. Besides, properties of gas flow hydrate formation in the pipeline depends on the profile of the flowline, presence of reduced areas, outputs and branches, soil temperature and heat exchange. In most cases, hydrates in flowlines are formed in places of concentration of local supports, lower sections of the route, surface sections, etc.

In gas storage facilities formation of hydrates at the gas collection point is most often observed during gas throttling through the adjustable choke. This is observed in gas storage facilities, where wells have high reservoir pressures. Also, hydrate formation is observed in areas of other local resistances, for example, on a common manifold entering the cleaning facility. After cleaning and dehydrating gas, hydrate formation in the gas storage facility is not observed.

We present the scheme of gas movement in the gas storage facility and the most likely places of hydrate formation in Figure 1.

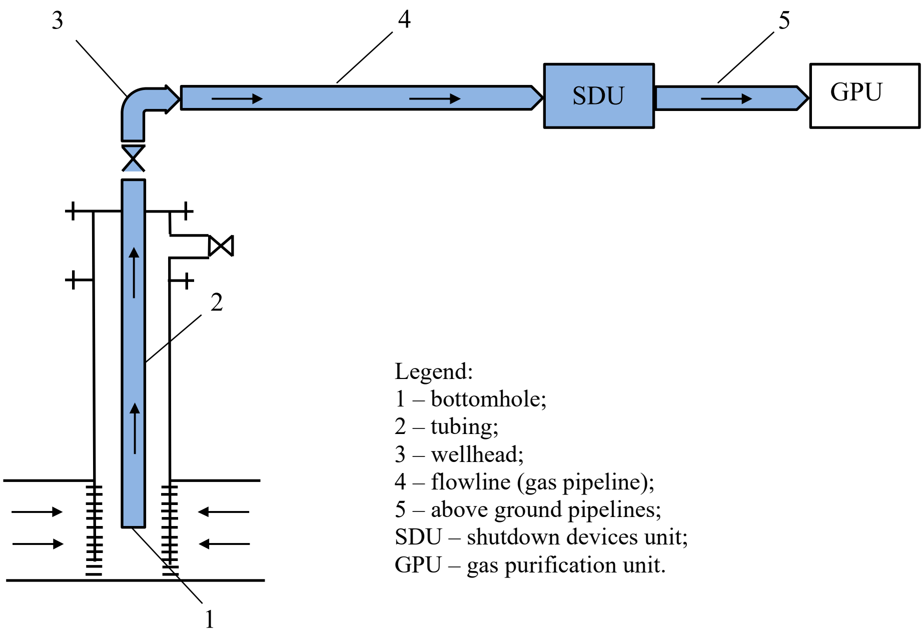

Fig. 1. The most problematic sections of hydrates deposition from the bottom to the gas collection point

At gas storage facilities, the greatest risk of hydrate formation occurs in the section 'bottomhole – wellhead – shutdown devices unit – gas purification unit' Figure 1.

Depending on the place of hydrates deposition during the operation of wells, their presence is caused by a change in the following parameters:

- in the wellbore hydrates deposition is determined by a decrease in pressure in the tubing space and an increase in the annulus, as well as a decrease in temperature on the wellhead compared to the technological mode;
- hydrates deposition along the flowline is determined by a decrease in pressure on the inlet of the gas collection point and an increase in working pressure on the wellhead of wells compared to technological mode;
- hydrates deposition on adjustable choke is determined by the increase in pressure on the inlet of the gas collection point compared to technological mode.

Therefore, in order to ensure the reliable operation of wells, control measurement of parameters of their operation (pressure, temperature, productivity) is performed in gas storage facilities. This allows to control the operation mode of wells and timely identify complications.

Scientists developed many different methods that allow us to predict hydrate formation. Using them in practice, employees of operational facilities can predict the likelihood of hydrates deposition. It should be noted that based on practical experience, it is known that – hydrates deposition is observed in different sections of pipelines. Thus this process is characterized as difficult to control.

In world practice, many methods were developed to prevent and eliminate hydrate formation to ensure the stable operation of wells and technological equipment both in gas and gas-condensate fields and in gas storage facilities. The authors made a classification of existing methods of preventing and eliminating hydrates into groups by the principle of action.

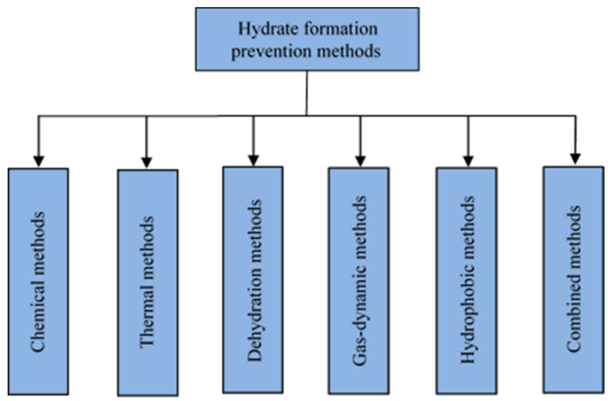

Fig. 2. Hydrate formation prevention methods

1) Prevention methods of hydrate formation can be divided into several main groups by the principle of operation (Fig. 2).

Chemical methods

Chemical methods for the prevention of hydrate formation include the use of inhibitors and other substances that change the properties of the gas-liquid mixture. Alcohols (methanol and methanol solution 60% – 85%) and glycols (ethylene glycol, diethylene glycol, triethylene glycol) are most often used as inhibitors. Complex inhibitors with different functional purposes are also used, that is, inhibitors of hydrate formation, corrosion, scale. Their use provides reliable equipment protection against corrosion and eliminates the possibility of formation and deposition of hydrates in wellbores and production communications. In addition, mixed inhibitors are used, that is, a mixture of several hydrate formation inhibitors. For example, methanol with a water solution of calcium chloride can be used. Less commonly, the fluid is used:

a) formation of water with high mineralization. For the use of such water, the following needs to be determined in advance: freezing point, salt composition, the possibility of precipitation during cooling, conditions for hydrate formation, etc. Thus, if the mineralization of formation waters is less than 40 g/l (density is less than 1.03 g/cm^3), then the effectiveness of such formation waters as an inhibitor is low, and it is inappropriate to use them [18];
b) calcium chloride solution with 30-35% concentration that is not toxic;
c) bischofite solution is used (crystalline hydrate magnesium chloride). While mixing of bischofite solution with formation waters of any degree of mineralization and ionic composition, there is no formation of insoluble sediments. Using this easily soluble salt ($MgCl_2$), a water solution with a density of 1250 kg/m^3 can be obtained with a crystallization temperature below minus 16°C. Hence, both bischofite solution and its mixture with formation water can serve as hydrate formation inhibitors;
d) surfactants are used to reduce the likelihood of hydrate formation.

To supply inhibitors and other substances in the well and gas pipeline, various methods are used:

- supply of hydrate inhibitor to the wellhead through inhibitor pipelines using dosing pumps. This method is effective but requires constant monitoring of pipeline integrity. Supply of hydrate formation inhibitor is possible, both constant and periodic;
- periodic injection of hydrate formation inhibitor using mobile cement pumping units into wells and their flowlines. This method requires periodic delivery of special equipment to the wellhead. The frequency of injection of hydrate formation inhibitor is set for each well separately, depending on the length of flowline and parameters of its operation;
- installation of inhibitor tanks on the wellhead of the well. Complications arise with the provision of dosed supply of hydrate formation inhibitor and the need for frequent tank filling;
- supply of methanol (other substances) through inhibitor pipelines to shutdown devices unit before adjustable choke using dosing pumps. This method is effective and is often used in gas storage facilities;
- supply of water solutions of surfactants is possible, both to bottomhole and flowline. Besides that, solid surfactants are used mainly in the form of briquettes supplied to the bottomhole. This method allows formed hydrates not to stick to the walls of pipes but to be transported along with gas.

Thermal methods

Thermal methods for hydrate formation prevention were widely used in gas industry. Thermal methods include:

- heating of local resistances (adjustable chokes, valves, etc.) with electric heating cable. This method is appropriate for separate sections and assemblies of the technological scheme. Advantages of this method are the possibility of remote control, speed of run-up to a set heat transfer mode, ease of use with an automated monitoring and control system, optimal electric power consumption is achieved;
- heating of tubing string and flowline with electric heating device lowered on the cable into the well inside the tubing string or laid along the flowline, where hydrates are often deposited;
- heating the well flowline on account of the circulation of hot thermal fluid. This method involves the installation of a heat exchange system along the gas pipeline, a thermal fluid heating unit and a pumping unit for its circulation;
- heating the tubing string of the well at the account circulation of hot thermal fluid. This method involves RIH with three strings of pipes and a rig up of surface equipment for heating and supply of thermal fluid into the well;
- increase in temperature of gas flow in the well by fire exhaust heaters that generate heat due to combustion of fuel-air mixture that is supplied into the well from outside. The disadvantage of bottomhole heaters is the difficulty in maintaining required parameters of the fuel-air mixture, as well as the mixing of flue gases with well production [19];
- use of heat of reservoir waters from below embedded horizons. This method involves RIH with casing string to the depth of shutdown of gas-bearing and water-bearing horizons, perforation of horizons, and equipment of Xmas tree with a double-row hanger. Initially, the first row of tubing is RIH to the gas-bearing horizon and then

the second row of pipes to the roof of the thermal pressure horizon [19];

- gas heating on the wellhead of wells before supplying into the flowline can be performed using a set of automated heating devices [18]. This complex includes the following: gas heaters, hydrate formation inhibitor injection unit, automation protection system and other equipment;
- a heat-insulating layer is applied to the outside surface of the tubing, flowline, and surface pipelines that reduces heat exchange during gas flow movement. For example, for a flowline or surface pipelines, a heat-insulating layer of polyurethane and other substances can be applied;
- gas heating with heat exchangers. The feasibility of installing heat exchangers needs to be determined subject to the presence of hot thermal fluid.

Dehydration methods

Dehydration methods for the prevention of hydrate formation are characterized by a different principle of action. Dehydration methods include:

- dehydration of gas from moisture by absorption, that is, the release of liquid hydrocarbons and water by absorbent liquids (glycols, diethylene glycols) or adsorption at cost absorption by solids (silica gels, activated carbon, zeolites, etc.). This method is effective, but it is used after gas purification in separation equipment [20,21];
- dehydration of gas from moisture by low-temperature separation. This method is effective, but there are certain conditions for its use – the presence of wells with high working pressure or installation of additional equipment, such as refrigeration machines, a low-temperature turbo expander, etc.;
- gas purification from moisture using separation equipment. This method provides gas purification from mechanical impurities and liquid phase at the cost of their entry into separators of various designs;
- use of devices for fluid drainage. This method involves the installation of various devices for fluid drainage: condensate collectors, expansion chambers, drips, etc. These devices have both advantages and disadvantages. Advantages include simple design and relatively small investments. They are installed on gas pipelines in places of the most likely fluid accumulation, including lowered areas. Instead, disadvantages include performing periodic maintenance to extract fluid since fluid accumulation can create additional local resistances and adversely affect the gas volume being transported.

Gas-dynamic methods

Gas-dynamic methods are often used in practice:

- ensuring hydrate-free mode of operation of wells and their flowlines by maintaining necessary thermobaric conditions under which hydrates are not formed. This method involves control of temperature and pressure that allows choosing the needed mode without hydrate formation based on industrial studies of wells;
- creation of high-speed gas flow in the flowline. This method is a temporary change in the technological mode of wells operation that contributes to an increase in the speed of movement of gas-liquid flow for recovery of liquid and hydrates to the gas collection point.

Hydrophobic methods

Hydrophobic methods for preventing hydrate formation involve using materials that cover the inside space of pipelines or are entered into gas flow in the liquid phase and prevent hydrates deposition on the walls of gas pipelines. These include:

- use of pipes with a special coating that reduces the roughness of the inside surface of the metal. This method is appropriate at the design and construction stages of new gas pipelines;
- supply to the inside space of tubing or into the flowline of liquid compounds containing substances with hydrophobic properties (oil with a significant content of asphaltenes and resins). This method involves the generation of a film on the walls of the pipe that reduces the likelihood of hydrates deposition.

The use of methods for preventing hydrate formation does not exclude the possibility of their formation and deposition in gas industry equipment due to the influence of various objective and subjective factors. In practice, various methods are used to eliminate hydrate formation. The use of these methods is aimed at the destruction of hydrates deposited in gas pipelines and equipment.

Combined methods

Combined methods of hydrate formation prevention involve using various methods (chemical, thermal, dehydration, gas-dynamic) in different sequences.

2) Methods for eliminating hydrate formation can be divided into several main groups according to the principle of action (Fig. 3).

Thermobaric methods

Thermobaric methods for hydrates elimination involve a decrease in pressure in places of their formation. To do this, perform a partial reduction in pressure at one of sections in order to increase gas velocity and take hydrates to the pit or separation equipment. In the case of the formation of a hydrate cork in a gas pipeline and the impossibility of its removal by blowing, a decrease in pressure to the atmospheric one is performed. For this, the following actions are performed:

- partial pressure decrease (blowing the well, flowline). This method is effective; it involves a partial decrease in pressure but leads to significant gas losses and well downtime;
- decrease in pressure (blowing) of the flowline to atmospheric pressure at the cost of its shutdown at the shutdown devices unit of the gas collection point, and then opening the shutoff valves to the pit of the well. This method is effective; it involves a unilateral reduction in pressure to atmospheric one that facilitates the decomposition of hydrates but is characterized by gas losses;
- decrease in pressure (blowing) of the flowline to atmospheric pressure at the account of its shutdown at the shutdown devices unit of the gas collection point, and then opening shutoff valves to the pit of the well and to the flare line of the gas treatment plant. This method is effective; it involves a bilateral decrease in pressure to atmospheric one that allows reducing the duration of hydrates decomposition and leads to additional gas losses;
- decrease in pressure (blowing) of the flowline to atmospheric pressure and supply of high-pressure gas. This method is effective; it differs from the previous in two that after decreasing pressure, high-pressure gas is supplied to the atmospheric one from the gas treatment plant to take out residues of possible hydrates to the pit of the well with the high-speed flow , but gas losses characterize it.

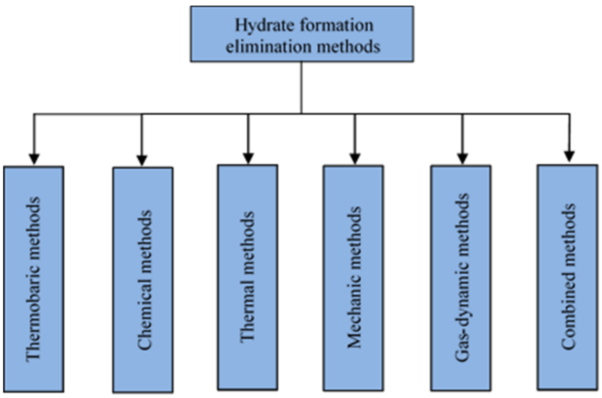

Fig. 3. Hydrate formation elimination methods

<u>Chemical methods</u>

Chemical methods involve the periodic injection of hydrate inhibitors into wells and their flowlines using mobile pumping units, and then gas supply for its locating directly into the place of hydrates deposition. This method is effective if high-pressure gas is available. The frequency of injection of a hydrate formation inhibitor is set for each well individually.

<u>Thermal methods</u>

Thermal methods are often used in practice. These include:

- heating of hydrate formation places of surface sections with hot water. This measure is effective in case of availability and a small area of the gas pipeline;
- heating the place of hydrate formation with the help of steam from a mobile steam generating unit. This measure is effective, and it is used both in the well and technological equipment of gas treatment plants.

<u>Mechanical methods</u>

Mechanical methods are rarely used in practice. These include:

- in gas wells, the hydrate cork that can reach a considerable length is drilled out in tubing. This method is high-cost;
- provided that a hydrate cork of considerable length is formed, windows are cut out in the pipe and methanol is poured through them, and then these windows are welded. This method is characterized by long-term downtime of wells.

<u>Gas-dynamic methods</u>

- squeezing with high-pressure gas from wells. This method is effective in case there are wells with high working pressure;
- supply of heated high-pressure gas from the gas treatment unit to the flowline. A complex implementation technology characterizes this method.

<u>Combined methods</u>

- in case of hydrates deposition in the tubing space of a well, it is put into production through annulus space and the mode that ensures the highest gas temperature is set. As a result of heating of production string and Xmas tree with warm gas, hydrates can decompose [21]. In practice, this method does not always have a positive result;
- provided that hydrates are deposited in the tubing space of the well, first methanol is injected, and then the well is put into production through annular space. Owing to the use of this method, as a rule, a positive result is obtained;
- either a partial decrease in pressure in the flowline is performed, or a decrease to atmospheric pressure in various ways, and then methanol is injected into the pipeline on the wellhead and the well production is renewed. This method is effective but additional gas losses characterize it;

- either a partial decrease in pressure in the flowline or decrease in atmospheric pressure in different methods and then injection of methanol into the pipeline from the gas treatment unit and supply of high-pressure gas to squeeze methanol and destroy possible hydrates to the pit of the well. After that, the well operation is resumed. This method is effective but is characterized by additional gas losses.

Taking into account the above-mentioned methods of prevention and elimination of hydrate formation for the conditions of gas storage facilities in Ukraine, the following were arranged as the most appropriate to apply:

- heating of adjustable chokes on the shutdown devices unit of the gas collection point with electric heating cable;
- heating places of hydrates deposition of surface section at gas collection point with the help of hot water;
- heating places of hydrate formation with steam from a mobile steam unit;
- periodic methanol injection through inhibitor lines using dosing pumps from the gas collection point to the wellhead into annulus space and/ or into flowline;
- periodic supply of methanol through inhibitor pipelines using pumps from the gas collection point to the shutdown devices unit before adjustable choke and/ or gas collection header, technological equipment;
- periodic injection of glycol or diethylene glycol by inhibitor lines using pumps from gas collection point to the wellhead into annulus space and/ or into flowline;
- method of partial pressure decrease (blowing of a well, flowline, gas collector manifold, etc.);
- decrease in pressure (blowing) of flowline to atmospheric pressure at cost of its shutdown on the shutdown devices unit of the gas collection point, and then opening the shutoff valves to the pit of the well.

Practical application of the above methods of prevention and elimination of hydrate formation leads to additional gas losses, as well as, in separate cases, can lead to negative consequences.

Therefore, taking into account the importance of the problem, the authors of the work recommend carrying out an integrated approach to ensure accurate control of the operation mode of wells and gas collection points that provides for the following:

- to ensure automatic monitoring of operation parameters of wells of the gas storage facility (pressure and temperature). To implement this, it is advisable to install pressure and temperature sensors with the output of working parameters to the automated workplace of the dispatcher, geologist and shift personnel (Fig. 4).

Due to this it is possible to monitor changes in thermobaric parameters and take timely measures to prevent hydrate formation [22];

- determine pressure losses in flowlines under different modes of wells operation and choose the optimal mode;
- determine probable places of the most frequent hydrates deposition in wells and technological equipment of gas storage facilities both based on results of theoretical and experimental studies;
- develop a software set for monitoring basic parameters of operation of the gas storage facility (gas flow rate, hydraulic resistance, hydraulic efficiency, etc.);

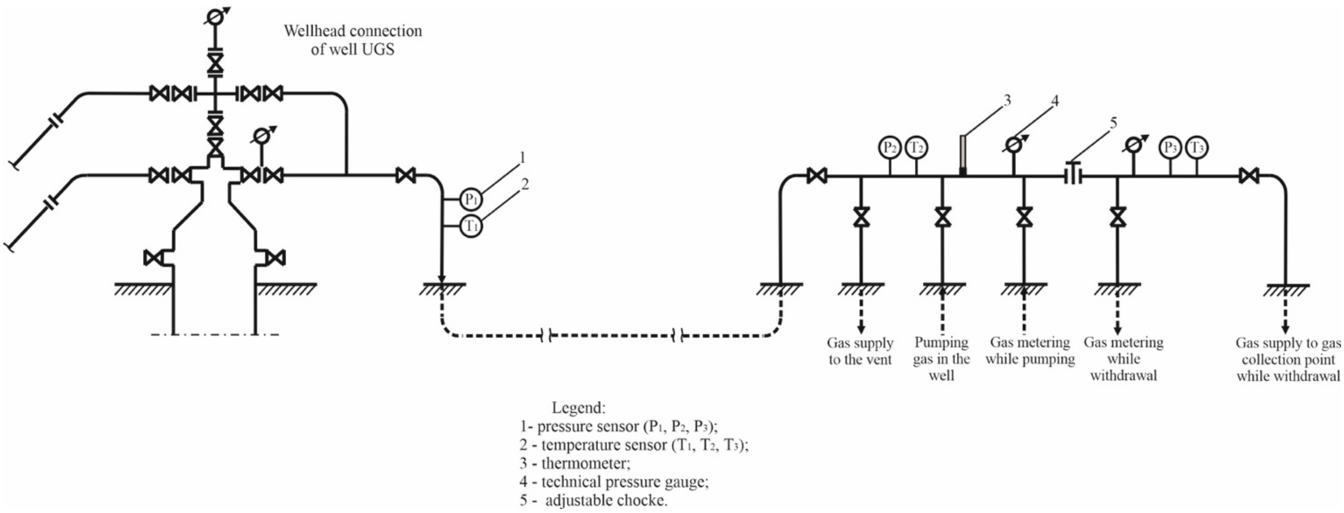

Fig. 4. Scheme of installation of pressure and temperature sensors on the wellhead and at the shutdown devices unit of the gas collection point

- prevent the accumulation of liquid contaminants in the inside space of flowlines, it is advisable to periodically clean them by creating high-velocity gas flow [23,24], using of surfactant solution [25,26], use of foam with different multiplicity [27,28] and other methods. The optimal method needs to be chosen based on experimental study.

4. Results and discussion

Prediction of complications (hydrate formation) during operation of wells

Currently, different approaches are known in the world practice to predict the possibility of complications, in particular, of hydrate formation, during the operation of wells at gas storage facilities. The powerful acceleration of digital technologies contributes to the development and wide application of new approaches in prediction using artificial intelligence technologies.

Thus, the work [29] highlights that to control and monitor the conditions of hydrate formation in the gas pipeline, the application of an approach using elements of artificial intelligence is proposed. This approach specified combines the modelling of thermodynamic flow parameters with the modelling of the dependence of these parameters on hydrate formation processes based on artificial neural networks. This allows improving the accuracy of forecasting hydrate formation. In the work [30] a complex model of an artificial neural network was developed to predict the temperature of hydrate formation. Owing to the use of artificial intelligence, it is possible to detect the formation of hydrates in time, subject to an approximation of significantly nonlinear dependencies using artificial neural network algorithms [31]. Thus, an artificial neural network is widely used for research and predicting the formation of hydrates in gas pipelines, a detailed analysis of which is carried out in work [32]. Therefore, the authors propose to use artificial neural network algorithms to solve the above-mentioned prediction problem.

The study of information processing algorithms based on artificial neural networks relates to the fact that the method of information processing by the human brain (where biological neural networks are implemented) is significantly different from methods used in the process of processing in existing computers built based on von Neumann architecture. The human brain is a rather complex system of information processing that is characterized by the parallel processing of nonlinear interconnected information with a large amount of uncertainty. It can organize its structural components, that is, neurons, in such a way in the network that they can perform specific tasks (images recognition, processing of sensory organs signals, motor functions, etc.) many times faster than the fastest modern computers can afford.

The concept of neuron development is associated with the plasticity of the human brain, that is, with the property of adjusting the nervous system according to environmental conditions. It is plasticity that plays a crucial role in neurons' work as basic elements of information processing in the human brain. Similarly, work is carried out in artificial neural networks with artificial neurons. In general, a neural network is a software and hardware device that simulates (somewhat simplified) a way for information processing and solving a specific problem by the brain. This network is usually implemented using electronic components or modelled by software that is installed on a computer or in-built microprocessor control unit. Obviously, neural networks take their power from the parallelization of information processing, as well as owing to the ability to self-study and, accordingly, improve the algorithm for specific input information processing. Practical application of artificial neural networks algorithms ensures the following advantages of systems, namely:

- nonlinearity of input-output relation;
- display of input information to output;
- adaptability;
- contextual information (the highest level of possible uncertainty of input data);
- scaling by standardization of disproportionate input data.

Neurons are basic elements of information processing in a neural network, at block-schematic diagram of Figure 5 a model of a neuron that is the basis of artificial neural networks. In this model there are three main components.

1) A set of synapses that are characterized by their weight factors of input information impact. The x_j signal on the input of synapse j that is supplied to one of the inputs of neuron k is multiplied by weight factor w_{kj}. The first index refers to the considered neuron, and the second to the synapse input end with which this weight factor is connected;
2) The adder processes input signals that are pre-weighted relative to the corresponding synapses (inputs) of the neuron;
3) The activation function normalizes the amplitude of output signal of a neuron according to a specific determined law. This feature is also called the compression function. Typically, the amplitude range of neural output is in intervals from 0 to 1 or from -1 to 1.

The neuron model in Figure 5 includes a threshold element that is denominated with the symbol b_k. This value reflects an increase or decrease in the input signal of a neuron that is not caused by the influence of controlled inputs and is supplied to adder input and further to the activation function [33].

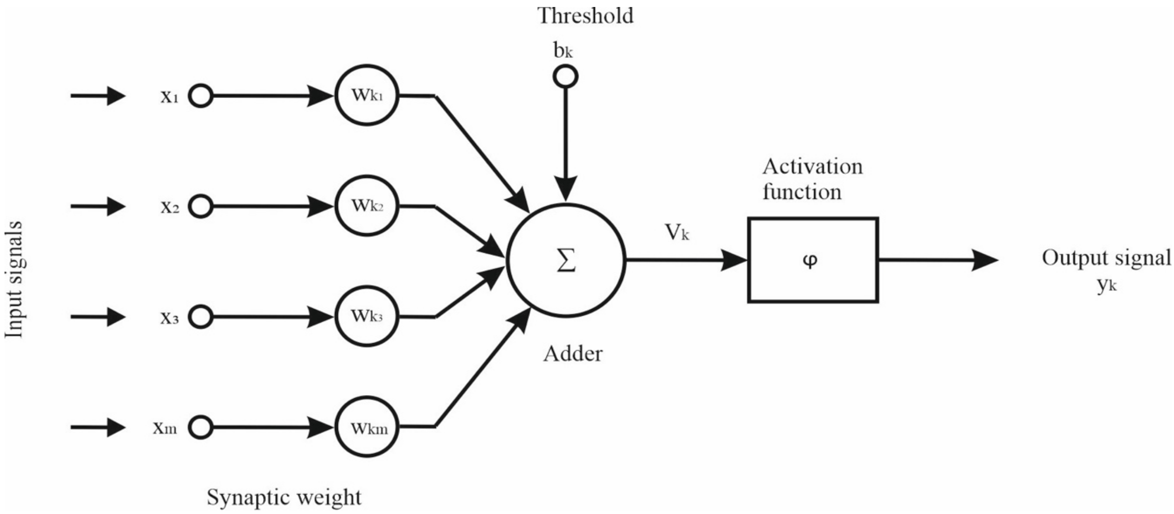

Fig. 5. Nonlinear model of a neuron as an element of an artificial neural network

We give the mathematical dependencies of neuron k functioning with the following two equations:

$$u_k = \sum_{j=1}^{m} w_{kj} \cdot x_j \tag{2}$$

$$y_k = \phi \cdot (u_k + b_k) = \phi \cdot v_k \tag{3}$$

where
x_1, x_2, x_3, x_m – input signals;
w_{k1}, w_{k2}, w_{k3}, w_{km} – synaptic weight factor of neuron k;
u_k – linear combination of input effects (signals);
b_k – threshold;
v_k – linear combination of input effects together with the threshold value;
φ – activation function;
y_k – output signal of neuron.

Using threshold b_k provides the effect of an affine output converter of linear adder u_k. In the model shown in Figure 5, the postsynaptic potential is calculated as follows:

$$v_k = u_k + b_k \tag{4}$$

Depending on what value threshold b_k takes, positive or negative, the value of v_k of neuron k changes accordingly.

Based on the above-mentioned and taking into account the number of information inputs (8 signals from sensors of technological parameters of flow in the pipeline) and one output (information about the absence of hydrate formation (0) or its presence on the adjustable choke (1) or inside space of flowline (2) to predict hydrate formation, the authors proposed to implement an algorithm for predicting hydrate formation based on an artificial two-layer Feed forward back propagation neural network. A neural network contains two layers of hidden neurons (the first layer has 8 neurons), and the second layer has 1 neuron. These neurons are connected between inputs of information and by synaptic relationships with corresponding weight factors. Since the structure of a two-layer artificial neural network at the simulation stage was already set by us, the calculation of network parameters essentially consists of the calculation of weight factors that optimally ensure compliance with the functioning of the hydrate formation prediction model.

To implement the model of neural network prediction, we propose to use actual data of wells operation mode at the control points of the pipeline, at sections in which hydrate formation is possible (Tab. 1). Figure 4 presents a schematic of pressure and temperature sensors placed on the wellhead and the shutdown devices unit of the gas collection point. Information from these sensors is the input information for the artificial neural network being developed both at the stage of its creation and then at the stage of its operation in the composition of the hydrate formation prediction system. Figure 6 proposes a schematic for transmitting information from pressure and temperature sensors to the device for its collection and transmission for storage (archiving) in memory of servers that implement cloud services for storage/processing/display of information) for further use by the algorithm of artificial neural networks. Owing to the implementation of this measure, the performance indicators of wells, in particular, pressure and temperature, will be supplied through radio channel from sensors to the device of information collection and transmission, and then through Internet communication, will be stored in the cloud and later in the database on the server computer. This will allow using of actual data to perform calculations and predict hydrate formation.

Table 1.
Experimental industrial input data of technological parameters for the algorithm of an artificial neural network at the stage of its training (selection of weight factors)

No. Well	Wellhead pressure, kgf/cm^2	Wellhead temperature, °C	Pressure on inlet of gas collection point, kgf/cm^2	Temperature on inlet of gas collection point, °C	Pressure after adjustable choke, kgf/cm^2	Temperature after adjustable choke, °C	Rate of the well, ths. m^3/day	Pressure in gas pipeline, kgf/cm^2	Note
1	99.0	20.0	97.2	14.0	28.0	-6.9	206.705	23-28	Mode before hydrates
1	99.5	19.5	98.3	13.2	27.8	-5.8	198.205	23-28	Hydrate on adjustable choke
1	99.8	19.0	98.5	13.0	27.6	-5.3	193.135	23-28	Hydrate on adjustable choke
2	92.6	17.5	90.7	12.0	26.6	-5.2	178.879	23-28	Mode before hydrates
2	92.9	17.0	92.0	10.8	26.0	-4.4	172.326	23-28	Hydrate on adjustable choke
2	93.3	16.8	92.3	10.2	25.8	-4.2	169.300	23-28	Hydrate on adjustable choke
3	59.0	13.0	52.6	8.0	26.9	-3.7	82.359	23-28	Mode before hydrates
3	60.1	12.5	50.8	7.0	26.0	-2.1	76.241	23-28	Hydrate in flowline
3	60.4	12.0	50.0	6.0	25.8	-1.8	72.112	23-28	Hydrate in flowline
4	62.5	14.0	58.5	7.2	28.0	-2.9	118.303	23-28	Mode before hydrate
4	63.2	13.6	56.1	6.0	27.7	-1.8	113.835	23-28	Hydrate in flowline
4	63.6	13.0	55.5	5.5	27.2	-1.2	109.865	23-28	Hydrate in flowline

Description of the method of prediction implementation using a neural network.

The essence of the method of hydrate formation prediction using an artificial neural network is that at the first stage, in MATLAB software environment, using the nntool function, a software module of a two-layer artificial neural network of Feed forward backprop type with a random set of weight factors is created (Fig. 7). The selection of the basic type of neural network, as a two-layer network of Feed forward backprop is due to a number of factors: 1) relatively limited volume of the training set of reliable data of technological parameters at the moment of the research; 2) positive results of adaptation of predicting results using the specified type of neural network on data that were not used in the training process and 3) the possibility of additional training of the neural network on new data without changing the structure of the network in the process of its use to predict hydrate formation.

Research in order to optimally select the neural network type for the task of predicting hydrate formation is the target of further research of technologies based on artificial intelligence to predict hydrate formation in the technological pipelines of underground gas storage facilities.

In the second stage, using the ‘train’ function, the neural network is trained on input and, accordingly, output data, an example of which is given in Table 1. The result of

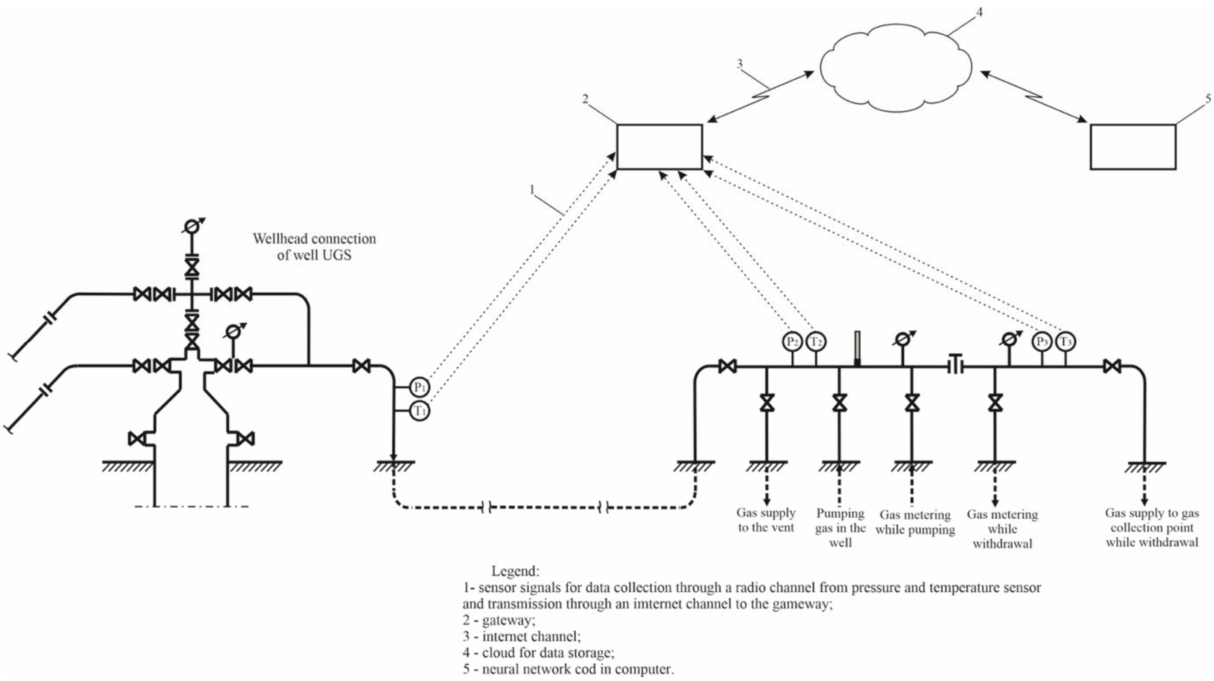

Fig. 6. Scheme of information transmission from pressure and temperature sensors to device and storage in the cloud for further use by the neural network

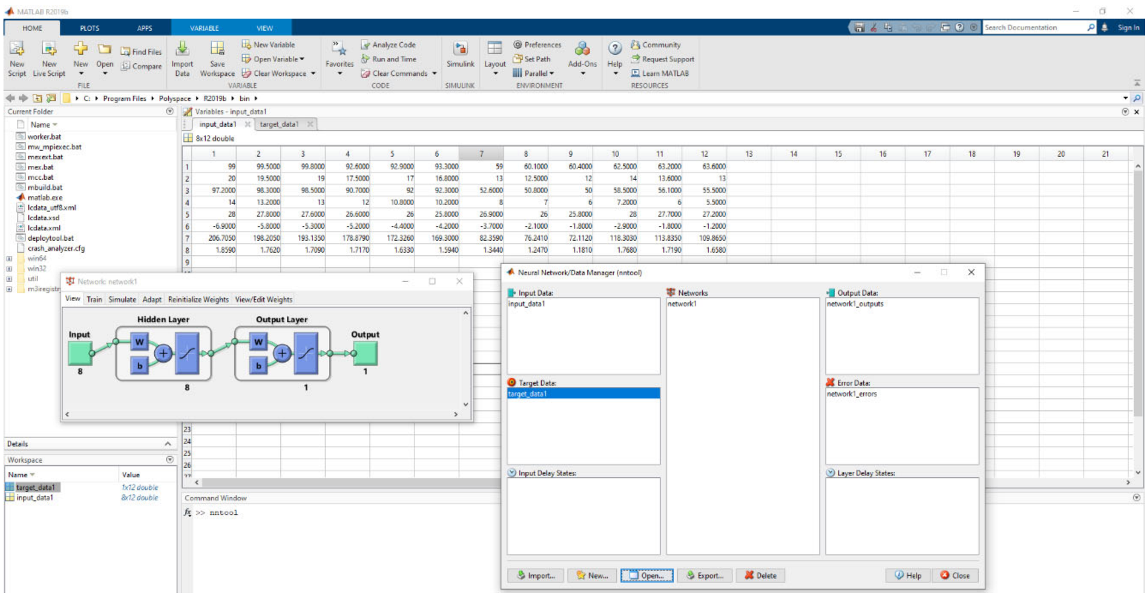

Fig. 7. Main window of MATLAB software environment with an input data set (variable input_data1) and a training set of data (variable target_data1) and with overlayed windows of Neural Network Data/Manager (nntool function) and the function of creating Network1

training by iterative selection is to receive weight factors of the neural network being developed for all its neurons (Fig. 8).

Obtained factors, provided that they are used in an artificial neural network, allow the device-calculator that implements a neural network, or a program that implements a neural network on a PC, to predict the beginning of hydrate formation process at two control points of the pipeline. In the third stage, an artificial neural network is used as means of prediction of hydrate formation with the ability to refine weight factors during its operation (Fig. 9) subject to receiving additional updated data, as an input set, for modifying the coefficients and accordingly, improving the algorithm for predicting by a artificial neural network. In the absence of new data for additional training of an artificial neural network, it is used as a computing too, that, on the basis of input data on the current above mentioned selected technological parameters of fluid in the pipeline, ensures the output values in the range from 0 to 1 (or from 0 to 100%), that indicates the probability of hydrate formation in the controlled section of the pipeline.

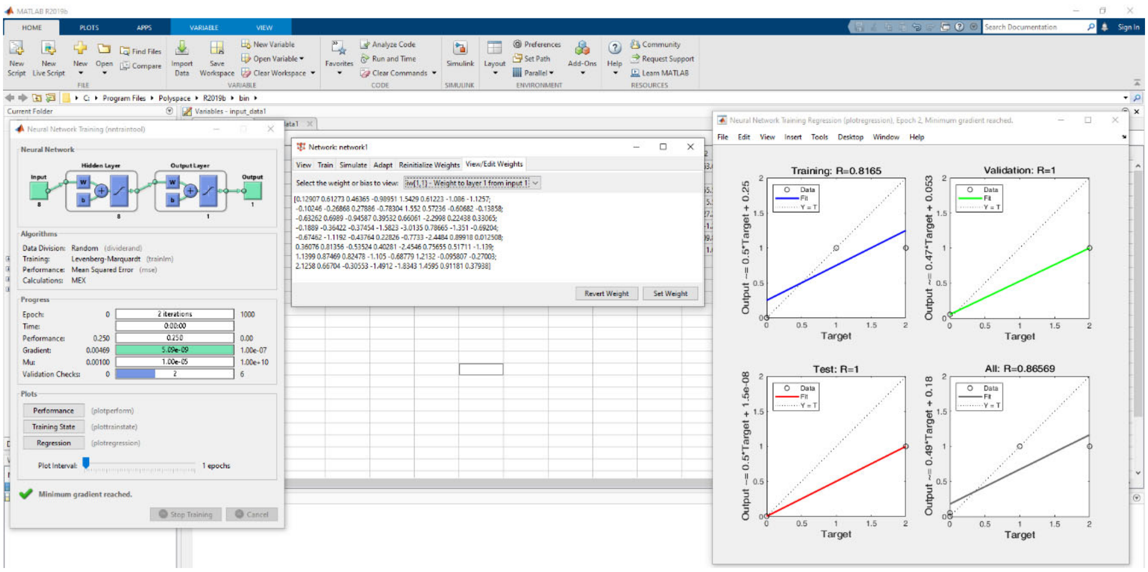

Fig. 8. The main window of MATLAB software environment with results of development of neural network Network1 in the form of displayed working windows: on the left - Neural Network Training (nntraintool function); in the centre – weight factors of the first layer of neurons of neural network Network1 that are calculated; on the right – regression graphs and numerical data of the correlation coefficients of hydrate formation between experimental data and results of neural network for training, validation and test sets of input data

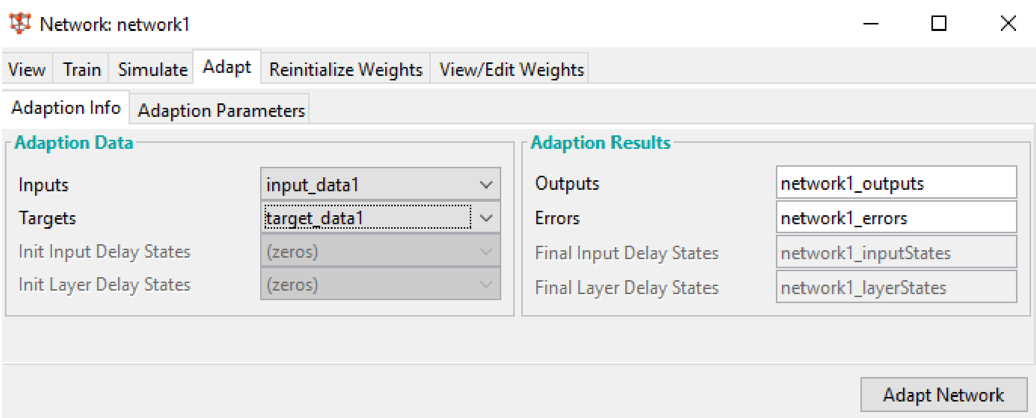

Fig. 9. The window of MATLAB software, where a two-layer neural network Network1 is created by input data set in Adapt tab, and where it is possible to add new, both input data of technological parameters and, accordingly, data on formation or non-formation of hydrates in different parts of the pipeline and, thus, ‘additional training’ – to improve the neural network by adjusting previously calculated weight factors of neurons of artificial neural network

So, this means of prediction objectively increase the reliability of results obtained in the process of prediction and system functioning.

5. Conclusions

1. The work addresses basic methods of prevention and elimination of hydrate formation that is used in practice to ensure the reliable operation of wells during gas production from the productive horizon. Conditional classification of methods into different groups according to the principle of action was performed. Methods of prevention and elimination of hydrate formation that is often used in gas storage facilities in Ukraine, are presented.
2. Authors proposed to carry out an integrated approach to ensure a stable mode of operation of wells and gas collection point under conditions of hydrates deposition, in particular: to ensure automatic monitoring of well operation parameters (pressure and temperature) of gas storage facility by installation of pressure and sensors with output of working parameters to automated workplace of dispatcher, geologist and shift personnel; choose the optimal mode of wells operation with minimal pressure losses; to determine the likely places of the most frequent deposition of hydrates in wells and technological equipment of gas storage facility, both according to the results of theoretical and experimental studies; to develop a software package to control main parameters of gas storage operation (gas flow velocity, hydraulic resistance, hydraulic efficiency, etc.); to prevent accumulation of liquid contaminants in inside space of flowlines, it is advisable to periodically clean by creating a high-velocity gas flow, use of surfactant solution, foam swab and other methods. This will allow taking timely decisions on application of measures to prevent hydrate formation.
3. The authors proposed to use of artificial intelligence technologies to solve the problem of hydrate formation prediction in sections of pipelines of underground gas storage facilities. With this purpose a method for creation of an artificial neural network as an algorithm for processing of information from pressure and temperature sensors at control points of underground gas storage facilities and prediction of hydrate formation processes beginning in these points was developed. The specified neural network is a software product with weight factors calculated in MATLAB environment and the ability to adapt parameters of the specified network to updated and supplemented input data during its operation.

   The developed methodology involves complementing and/ or updating data as an input set for modifying coefficients and, accordingly, improving the algorithm for predicting an artificial neural network. In the absence of new data for additional training of an artificial neural network, it is used as a computing tool that, on the basis of input data on the current above-mentioned selected technological parameters of fluid in the pipeline, ensures the output values in the range from 0 to 1 (or from 0 to 100%), that indicates the probability of hydrate formation in the controlled section of the pipeline.
4. In future, it is advisable to develop further and implement new technical solutions and technologies to improve the efficiency of the operation of gas storage facility to ensure the choice of optimal hydrate-free mode of wells operation. It is also advisable to develop and take measures to prevent their formation, including through the introduction of modern intelligent systems for monitoring and controlling technological processes. Automating control of working parameters of gas collection system of gas storage facility allows not only to control conditions of hydrate formation, but also to determine optimal modes of wells operation.

References

[1] S. Matkivskyi, Increasing hydrocarbon recovery of Hadiach field by means of CO_2 injection as a part of the decarbonization process of the energy sector in Ukraine, Mining of Mineral Deposits 16/1 (2022) 114-120. DOI: https://doi.org/10.33271/mining16.01.114

[2] S. Matkivskyi, L. Khaidarova, Increasing the Productivity of Gas Wells in Conditions of High Water Factors, Proceedings of the SPE Eastern Europe Subsurface Conference, Kyiv, Ukraine, 2021, SPE-208564-MS. DOI: https://doi.org/10.2118/208564-MS

[3] S. Matkivskyi, O. Burachok, Impact of Reservoir Heterogeneity on the Control of Water Encroachment into Gas-Condensate Reservoirs during CO_2 Injection, Management Systems in Production Engineering 30/1 (2022) 62-68. DOI: https://doi.org/10.2478/mspe-2022-0008

[4] S. Matkivskyi, O. Kondrat, O. Burachok, Investigation of the influence of the carbon dioxide (CO_2) injection rate on the activity of the water pressure system during gas condensate fields development, E3S Web of Conferences 230 (2021) 01011. DOI: https://doi.org/10.1051/e3sconf/202123001011

[5] S. Matkivskyi, O. Kondrat, Studying the influence of the carbon dioxide injection period duration on the gas

recovery factor during the gas condensate fields development under water drive, Mining of Mineral Deposits 15/2 (2021) 95-101.
DOI: https://doi.org/10.33271/mining15.02.095

[6] S. Matkivskyi, O. Kondrat, The influence of nitrogen injection duration at the initial gas-water contact on the gas recovery factor, Eastern-European Journal of Enterprise Technologies1/6(109) (2021) 77-84. DOI: https://doi.org/10.15587/1729-4061.2021.224244

[7] Ya.V. Doroshenko, G.M. Kogut, I.V. Rybitskyi, O.S. Tarayevs'kyy, T.Yu. Pyrig, Numerical investigation on erosion wear and strength of main gas pipelines bends, Physics and Chemistry of Solid State 22/3 (2021) 551-560. DOI: https://doi.org/10.15330/pcss.22.3.551-560

[8] E.G. Hammerschmidt, Formation of gas hydrates in natural gas transmission lines, Industrial and Engineering Chemistry 26/8 (1934) 851-855. DOI: https://doi.org/10.1021/ie50296a010

[9] S.Sh. Byk, Yu.F. Makogon, V.I. Fomina, Gas hydrates, Khimina, Moscow, 1980 (in Russian).

[10] V.G. Vasilyev, V.I. Yermakov, I.P. Zhabreyev, Gas and gas and condensate fields. Reference book, Nedra, Moscow, 1983 (in Russian).

[11] S.T. Guliyants, G.I. Yegorova, A.A. Aksentiyev, Physico-chemical features of gas hydrates: Study guide, Tyumen State Oil and Gas University, Tyumen, 2010 (in Ukrainian).

[12] Yu.F. Makogon, G.A. Sarkisyants, Prevention of hydrate formation while production and transportation of gases, Nedra, Moscow, 1966 (in Russian).

[13] Rules of gas and gas and condensate fields development, Nedra, Moscow, 1971 (in Russian).

[14] G.A. Zotov, Z.S. Aliyev (eds), Guidelines for comprehensive study of gas and gas condensate formations and wells, Nedra, Moscow, 1980 (in Russian).

[15] A.I. Gritsenko, Z.S. Aliyev, O.M. Yermilov, V.V. Remizov, G.A. Zotov. Guidelines for wells research, Nauka, Moscow, 1995 (in Russian).

[16] V.I. Dmytrenko I.G. Zezekalo, O.O. Ivankiv; applicant and owner – Ukrainian State Geological Exploration Institute. No. 32436 Patent Ukraine, МПК(2006) E21B 43/11. Complex inhibitor of hydrate formation and corrosion OV-07, No. u 2008 01115; application 30.01.2008; published 12.05.2008, Information Letter No. 9.

[17] N.N. Nguyen, R. Berger, H.-J. Butt, Premelting-induced agglomeration of hydrates: theoretical analysis and modeling, ACS Applied Materials and Interfaces 12/12 (2020) 14599-14606.
DOI: https://doi.org/10.1021/acsami.0c00636

[18] B.V. Degtyaryev, E.B. Bukhgalter, Combating hydrates while producing gas wells in the northern regions, Nedra, Moscow, 1976 (in Russian).

[19] B.V. Degtyaryev, G.S. Lutoshkin, E.B. Bukhgalter, Combating hydrates while producing gas wells in the regions of the North (practical manual), Nedra, Moscow, 1969 (in Russian).

[20] V.S. Boiko, R.M. Kondrat, R.S. Yaremiychuk, Reference book on oil and gas business, Ivano-Frankivsk National Technical University of Oil and Gas, Lviv, 1996 (in Ukrainian).

[21] Yu.P. Korotayev, R.D. Margulov (eds), Production, treatment and transportation of natural gas and condensate: Reference guide in 2 volumes, Volume I, Nedra, Moscow, 1984 (in Russian).

[22] V.B. Volovetskyi, Ya.V. Doroshenko, A.O. Bugai, G.M. Kogut, P.M. Raiter, Y.M. Femiak, R.V. Bondarenko, Developing measures to eliminate of hydrate formation in underground gas storages, Journal of Achievements in Materials and Manufacturing Engineering 111/2 (2022) 64-77.
DOI: https://doi.org/10.5604/01.3001.0015.9996

[23] V.B. Volovetskyi, Ya.V. Doroshenko, G.M. Kogut, A.P. Dzhus, I.V. Rybitskyi, J.I. Doroshenko, O.M. Shchyrba, Investigation of gas gathering pipelines operation efficiency and selection of improvement methods, Journal of Achievements in Materials and Manufacturing Engineering 107/2 (2021) 59-74. DOI: https://doi.org/10.5604/01.3001.0015.3585

[24] V.B. Volovetskyi, A.V. Uhrynovskyi, Ya.V. Doroshenko, O.M. Shchyrba, Yu.S. Stakhmych, Developing a set of measures to provide maximum hydraulic efficiency of gas gathering pipelines, Journal of Achievements in Materials and Manufacturing Engineering 101/1 (2020) 27-41.
DOI: https://doi.org/10.5604/01.3001.0014.4088

[25] V.B. Volovetskyi, Ya.V. Doroshenko, G.M. Kogut, I.V. Rybitskyi, J.I. Doroshenko, O.M. Shchyrba, Developing a complex of measures for liquid removal from gas condensate wells and flowlines using surfactants, Archives of Materials Science and Engineering 108/1 (2021) 24-41.
DOI: https://doi.org/10.5604/01.3001.0015.0250

[26] V.B. Volovetskyi, Ya.V. Doroshenko, S.M. Stetsiuk, S.V. Matkivskyi, O.M. Shchyrba, Y.M. Femiak, G.M. Kogut, Development of foam-breaking measures after removing liquid contamination from wells and flowlines by using surface-active substances, Journal of Achievements in Materials and Manufacturing Engineering 114/2 (2022) 67-80.
DOI: https://doi.org/10.5604/01.3001.0016.2157

[27] V.B. Volovetskyi, Ya.V. Doroshenko, O.S. Tarayevs'kyy, O.M. Shchyrba, J.I. Doroshenko, Yu.S. Stakhmych, Experimental effectiveness studies of the technology for cleaning the inner cavity of gas gathering pipelines, Journal of Achievements in Materials and Manufacturing Engineering 105/2 (2021) 61-77.
DOI: https://doi.org/10.5604/01.3001.0015.0518

[28] V. Volovetskyi, Ya. Doroshenko, O. Karpash, O. Shchyrba, S. Matkivskyi, O. Ivanov, H. Protsiuk, Experimental Studies of Efficient Wells Completion in Depleted Gas Condensate Fields by Using Foams, Strojnícky Časopis – Journal of Mechanical Engineering 72/2 (2022) 219-238.
DOI: https://doi.org/10.2478/scjme-2022-0031

[29] N. Rebai, A. Hadjadj, A. Benmounah, A.S. Berroukc, S.M. Boualleg, Prediction of natural gas hydrates formation using a combination of thermodynamic and neural network modeling, Journal of Petroleum Science and Engineering 182 (2019) 106270. DOI: https://doi.org/10.1016/j.petrol.2019.106270

[30] A.N. El-hoshoudy, A. Ahmed, S. Gomaa, A. Abdelhady, An Artificial Neural Network Model for Predicting the Hydrate Formation Temperature, Arabian Journal for Science and Engineering 47 (2022) 11599-11608. DOI: https://doi.org/10.1007/s13369-021-06340-w

[31] Y. Seo, B. Kim, J. Lee, Y. Lee, Development of AI-Based Diagnostic Model for the Prediction of Hydrate in Gas Pipeline, Energies 14/8 (2021) 2313. DOI: https://doi.org/10.3390/en14082313

[32] S.J.A.K. Sahith, S.R. Pedapati, B. Lal, Application of Artificial Neural Networks on Measurement of Gas Hydrates in Pipelines, Test Engineering and Management 81 (2022) 5769-5774.

[33] S.S. Haykin, Neural Networks: A Comprehensive Foundation, Second Edition, Prentice-Hall of India Pvt. Limited, India, 1999.