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APPLICATION OF ULTRA-HIGH FREQUENCY ELECTROMAGNETIC RADIATION ENERGY TO INCREASE THE EFFICIENCY OF GAS PREPARATION PROCESSES IN HYDRATE FORMATION CONDITIONS

The effective operation of modern gas systems requires new approaches to combat hydrate plugs, which limit the flow and cause emergency shutdowns. The object of research is the process of formation and destruction of gas hydrates in industrial pipelines under the influence of microwave radiation. The research is aimed at solving the problem of excessive use of methanol to combat hydrates. This reagent is very toxic and expensive, and its real costs in the fields of Ukraine are often 15–20% higher than the norm due to outdated dosing methods.

The results of the work are based on modeling the technological processes of the Machukhske field (Ukraine) in the Aspen HYSYS program. The most dangerous zone of hydrate formation was identified in a 20-meter section immediately after the throttle when the gas temperature drops to –30.11°C. To protect this unit, a new design of a removable insert with a magnetron has been developed, which provides thermodynamic decomposition of crystal hydrates by directly transferring the energy of the microwave field to water molecules in the flow volume.

A distinctive feature of the development is the creation of a resonant zone between the choke and the diaphragm, which allows concentrating the field and accelerating the dissociation of hydrates by 1.5–3 times compared to thermal heating. The optimized geometry of the diaphragm provides high wave reflection without a significant increase in the hydrodynamic resistance of the gas flow.

The practical value of the work lies in the possibility of integrating the developed design of the ultrahigh-frequency electromagnetic radiation device into low-temperature gas separation units and hydrocarbon collection systems with a complex temperature regime. The introduction of the device allows maintaining a stable hydrate-free mode of pipeline operation, reducing the consumption of chemical reagents and increasing the environmental safety of gas production in Ukrainian fields by minimizing the use of toxic methanol.

Keywords: *hydrates, low-temperature separation, microwave radiation, inhibitors, methanol, gas preparation, energy efficiency.*

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1. Introduction

Gas hydrates (methane, ethane, etc.) are crystalline compounds of water and gas that are stable at low temperatures and high pressures [1]. Their formation causes serious problems in the transportation of hydrocarbons [2].

During the extraction, collection, preparation and industrial processing of gas and oil, the formation of gas hydrates is observed in various sections of pipelines [3]. Depositing on the inner walls of pipes, hydrates sharply reduce their throughput and can lead to an emergency shutdown of the gas pipeline [4]. This leads to a decrease in the throughput of pipelines, and in some cases to their shutdown. Therefore, the elimination of hydrate formation during the extraction and transportation of hydrocarbon raw materials is one of the important and urgent problems.

In domestic and foreign practice, a universal method of combating gas hydrates in wells and pipelines has not been found to date. This is primarily due to the different conditions for the formation of gas hydrates in the hydrocarbon process, as well as the variety of well and pipeline designs [5].

Among the existing methods for preventing the formation of gas hydrates in hydrocarbon production, collection and preparation systems, and the use of chemical reagents is technologically and economically justified [2].

At present, methanol is mostly used at Ukrainian enterprises to prevent hydrate formation. However, it is toxic, explosive and quite expensive [6]. In addition, in practice, the actual consumption of methanol at gas production enterprises is often overestimated (in some cases by 15–20% or more) due to its irrational use, therefore, the question of optimizing its consumption and the most effective use in hydrocarbon raw material collection and preparation systems still arises [5].

The need to eliminate the formed hydrate deposits indicates a deviation from the regulatory operating mode and insufficient effectiveness of the protection system. There is a need to analyze existing methods for eliminating plugs in order to develop improved combined technologies for their prevention.

The choice of methods for eliminating hydrates is determined by the place of their accumulation, the amount and nature of the hydrate plug, the composition of the hydrate, as well as the available means of elimination.

Several methods are known for combating hydrate plugs that have already formed [4]: injection of inhibitors into gas pipelines; reducing pressure in the gas pipeline; heating the gas and local heating of hydrate deposition sites. Methyl alcohol (methanol), a solution of diethylene glycol (DEG), triethylene glycol (TEG) and a solution of calcium chloride can be used as inhibitors. The effectiveness of their use depends on the conditions of hydrate formation.

In case of partial blockage of the working section, when the movement of the gas flow is ensured, the elimination of hydrates is possible by transport through a coolant pipe or an inhibitor. The most difficult to eliminate are solid hydrate plugs that cover the entire cross-section of the pipeline. When determining the location of such a plug accumulation in any section of the pipeline, it is necessary first of all to disrupt the integrity of the hydrates, which is possible by heating the pipeline, supplying an inhibitor, or other methods [7].

The most accessible method of eliminating accumulated hydrates is the method of reducing pressure, which is widely used [8], but it takes a lot of time. Reducing pressure gives a positive effect in eliminating the hydrate plug, only at positive temperatures. At negative ambient temperatures, this method is ineffective.

The cheapest way to eliminate gas hydrate plugs is local heating of the gas pipeline section [9]. However, there is not always access to the necessary section of the gas pipeline. In addition, the gas hydrate plug melts near the walls of the pipeline and can move along the pipeline due to the pressure difference.

In recent decades, research has been intensified into the use of ultrahigh-frequency electromagnetic radiation (UHF EMR) as a method of intensifying hydrate dissociation [10].

The use of high-frequency (HF) and ultra-high-frequency (UHF) electromagnetic fields (EMF) energy for the destruction of gas hydrates has promising practical value [11] due to the specific features of the interaction of electromagnetic waves with dispersed systems [12] (selectivity, controllability and high heating rate, the possibility of conversion into other types of physical fields, etc.). Since the pipeline in radiophysical terms is a guiding system, due to the attenuation of electromagnetic wave energy along its entire length, this method is advisable to use when eliminating solid hydrate plugs [13].

Natural gas hydrates are characterized by a complex relative dielectric permittivity [14], i. e., they are lossy dielectrics [15].

In [16], the issue of melting paraffin plugs in oil pipelines using the H_{11} mode is considered. The issue of dissociation of gas hydrates by UHF radiation was considered in [17]. Calculations were performed for the E_{01} mode. In [18], the calculation of melting of paraffin plugs using the H_{01} mode of HMF radiation was considered. To consider the dissociation of gas hydrates in real gas pipelines of different diameters, it is necessary to take into account their operation in a multimode mode.

Dissociation of gas hydrates and melting of paraffins in wells under the influence of T-waves of HF radiation was considered in [19], however, the dependence of internal heat flows on the temperature of gas hydrate was not taken into account by the author, and the well was considered as an analogue of a coaxial line. In work [18], heat exchange along the pipeline was not taken into account, the change in heat sources due to hydrate melting was not taken into account, and the dissociation of hydrate during the passage of EM waves in it was not taken into account. In [19], the authors considered only the absorption of EM waves in the metal elements of the well (air-pumping pipe), and heat transfer from the air-pumping pipe to the hydrate occurs by thermal conductivity. With this method, energy supply is irrational because instead of heating gas hydrate or paraffin, all elements of the well are heated.

Calculations of gas hydrate dissociation and paraffin melting in [17] were performed only for a homogeneous medium inside the gas pipeline. However, with a stationary placement of a microwave emitter, part of the gas pipeline will be filled with gas and part with gas hydrate, i. e. the medium will be heterogeneous. In addition, this heterogeneity will change over time.

In [20], the results of laboratory studies are presented, which compare the dissociation of hydrate under microwave heating and when using hot water. The results obtained show that the use of UHF EMR can give faster dissociation and increase the gas yield, which experimentally proves the concept of GH dissociation under the influence of UHF EMR.

Microwave EMF irradiation accelerates the dissociation of natural and laboratory GH compared to traditional heating (hot water), and the dissociation rate depends on the power and frequency of EM radiation.

The results of experiments on a laboratory unit, which confirm the possibility of methane recovery from hydrate deposits using microwaves EMF are given in [21]. The method of extracting methane from a hydrate reservoir using microwave stimulation was experimentally verified on a laboratory scale. The studies were carried out in loose sediment from the South China Sea, using microwave radiation at a frequency of 2.45 GHz with an average specific power from 3 to 19 kW/m^2. It was found that hydrate saturation (15.5–54.5%), water saturation (40.7 and 70.4%), freezing and combination with a decrease in pressure affect heating, gas formation and the efficiency of GH dissociation. For example, the presence of ice reduces the efficiency of GH dissociation in the sediment compared to water-saturated under reduced pressure conditions. It was found that the hydrate layer located beyond the microwave penetration limit dissociates in an equilibrium state.

Laboratory attempts to use microwaves to decompose hydrates have shown an acceleration of dissociation by 1.5–3 times compared to traditional heating with hot water [22]. Direct heating of the hydrate phase provides a reduction in energy costs, while the speed of the process depends on the radiation power (300–900 W) and the exposure time. During the studies, the formation of two zones was recorded: active (maximum absorption) and inert, which occurs due to a decrease in humidity or reflection of waves [21].

Further work [22] supplemented the study using RF and plasma sources. The results show that in the range of 0.3–3 GHz, the efficiency of hydrate destruction increases with frequency up to a certain limit, after which saturation is observed due to the limited permeability of the waves [23].

In [24], modern complex physical models are presented that combine EMF heating and gas injection (for example, N_2) to increase the efficiency of extraction. Such models allow to perform design calculations and to apply the developed methodology in industry.

In work [25] the mathematical model of destruction of hydrate plugs in a pipeline when using a coaxial microwave source of EMR is proposed, the constructive details of the antenna, temperature distribution and efficiency of GH dissociation are given. The theoretical assessment of the efficiency of using such influence for unblocking gas pipelines from GH plugs is given.

A one-dimensional non-stationary mathematical model of heat transfer processes during the GH decomposition in a cylindrical pipeline under the action of heat sources distributed over the volume is presented. A numerical calculation algorithm is proposed. A mathematical expression for distributed heat sources generated by microwave radiation from a coaxially located microwave antenna is obtained. The device that creates microwave radiation is located along the axis of the pipe. Numerical studies of temperature fields and the dynamics of the decomposition of a gas hydrate plug for given pipe parameters and microwave radiation power are carried out. It is established that the decomposition time of a gas hydrate plug with a diameter of 0.3 m using a microwave source with a power of 300 W is approximately 40 hours.

Models of multi-physics processes [24] simultaneously take into account: absorption of electromagnetic energy depending on the dielectric properties of the medium; heat transfer and phase transitions; movement of gas, water and heat in a porous medium [25].

Numerical simulations show that at a power of 1 kW and a frequency of 2.45 GHz, the active dissociation zone can expand to several centimeters per minute, and the combination of microwave heating with nitrogen (N_2) injection provides an efficiency increase of 20–30%.

To solve the problem of destroying GH plugs in a gas pipeline, in [23] a coaxial microwave antenna was simulated, which allows local heating of hydrate plugs, ensuring a uniform temperature distribution along the axis of the pipeline.

In [24], the results of the simulation, including its verification, are presented. The proposed mathematical model can be applied in the case of using complex effects of various factors on gas hydrates.

Microwave heating technology is an effective method for the recovery of methane hydrates. However, the recovery of methane hydrates under the influence of microwave radiation is a complex set of physicochemical and thermal processes. In this research, a numerical framework is developed to investigate the multi-physics behavior of the electromagnetic field evolution, multiphase flow and heat and mass transfer during the recovery of methane hydrates using microwaves. The spatio-temporal evolution of the electric field strength, temperature, phase saturation and flow rate were simulated for the first time. In addition, parametric studies revealed the dependence of the dissociation and gas recovery efficiency on three critical factors: initial water saturation, microwave power and nitrogen injection rate. The results showed that the proposed framework effectively takes into account the synergistic interaction between the electric field evolution, heat and mass transfer and multiphase flow during the recovery of hydrates. Most importantly, the synergistic application of microwave heating and nitrogen injection significantly improved the efficiency of hydrate dissociation and methane recovery, especially under conditions of high initial water saturation. Increasing the microwave input power can significantly accelerate the dissociation of hydrates and improve the efficiency of methane recovery. In addition, although the increased nitrogen injection rate had a negative effect on the dissociation of hydrates, it improved the recovery efficiency [26]. This provides critical guidance for optimizing gas recovery strategies in the development of hydrates using microwave radiation.

The set of studies confirms that microwave electromagnetic radiation is a promising tool for the destruction of gas hydrates both in laboratory conditions and in engineering systems. The method provides effective conversion of electromagnetic energy into heat without intermediate carriers, allows to accelerate dissociation and reduce costs.

Analysis of literature data shows that for the correct calculation of the destruction of a gas hydrate plug in a gas pipeline using microwave radiation, it is necessary to take into account a number of factors: multimode of a real pipeline; heterogeneity of the dielectric medium; temperature dependence of volumetric heat flows in gas hydrate.

Modern studies confirm the technological feasibility of using electromagnetic influence to combat hydrates. The practical application of electromagnetic methods in the gas industry is based on the development of specialized systems for generating and directing energy directly to the hydrate formation zone.

In particular, in [27] the architecture of microwave antennas was substantiated and numerical modeling of dissociation processes was carried out to increase the efficiency of targeted heating. A systematic analysis of commercial approaches to the extraction and stimulation of hydrate deposits, presented in [28], identifies electromagnetic methods as a promising tool for process intensification.

In [29] the results of experiments on the influence of radiation of different ranges (MW/RF/UHF) on the stability of hydrates in comparison with traditional inhibition were systematized. The practical implementation of these methods is presented in the patent [30], which describes radiofrequency equipment for processing liquids, which provides volumetric heat release directly in the zone of possible plug formation.

In the known design [31], a throttling valve is installed in the pipeline section before the low-temperature separator, where the gas pressure and temperature decrease, as a result of which the separator separates heavy fractions (gas condensate), and the purified gas is then fed to the heat exchanger.

The main disadvantage of the design [31] is the possibility of active hydrate formation in the section of the gas pipeline from the throttling device to the low-temperature separator, since when the temperature decreases and the pressure is sufficiently high, favorable conditions for hydrate formation are created. To avoid hydrate formation in industrial-type installations, an additional amount of toxic and environmentally hazardous inhibitor (usually methanol) is introduced into the gas pipeline before this section [31].

Analysis of scientific sources and the results of modern research confirms that the use of ultrahigh-frequency electromagnetic radiation (UHF EMR) is one of the most promising methods for intensifying the dissociation of gas hydrates. The transition from general inhibition to localized UHF influence in critical zones of hydrate formation is a strategically important direction for increasing the reliability and environmental friendliness of hydrocarbon raw material preparation systems in Ukraine.

Thus, the chosen direction of research on the modernization of the device for preventing the formation and decomposition of gas hydrates inside a steel gas pipeline is an urgent scientific and technical task, the solution of which will allow to increase the reliability of the operation of wells and main networks in hydrate-hazardous modes.

The object of research is the process of formation and destruction of gas hydrates in industrial pipelines under the influence of microwave radiation.

The aim of research is to increase the efficiency of gas preparation processes under conditions of hydrate formation by using the energy of microwave radiation.

Research objectives:

1. To determine the critical zones of active hydrate formation in technological lines of low-temperature gas separation (on the example of Machukhske field, Ukraine) using computer modeling in the Aspen HYSYS environment.
2. To improve the device for microwave prevention of hydrate formation in industrial gas pipelines.

2. Materials and Methods

The research of methanol content in the technological lines of low-temperature gas separation plants was carried out using the Aspen HYSYS simulator (Aspen Technology, Inc., USA). The simulation was performed in the static simulation mode. Aspen HYSYS has built-in thermodynamic models, which, using the Hydrate Formation utility, allow to accurately predict the thermobaric conditions of hydrate formation in pipelines of gas production, processing and transportation facilities. This utility calculates the starting point of solid hydrate formation (structures I, II, H) using thermodynamic models. Predictions of the starting point of hydrate formation are based on the original hydrate equilibrium model proposed by van der Waals and Platteeuw, combined with the modification proposed by Parrish and Prausnitz [5].

An analysis of the operation of gas preparation facilities using low-temperature separation technology (LTS), where gas cooling is carried out due to the Joule-Thompson effect, was performed.

In thermodynamics, the Joule-Thompson effect describes the change in temperature of a real gas (as opposed to an ideal gas) during its expansion, which is usually caused by a decrease in pressure as it passes through a throttling device in the absence of heat exchange with the environment. During adiabatic expansion, the gas does work, losing internal energy, which leads to a decrease in temperature.

Fig. 1 shows a schematic diagram of the gas preparation process using the Joule-Thompson effect.

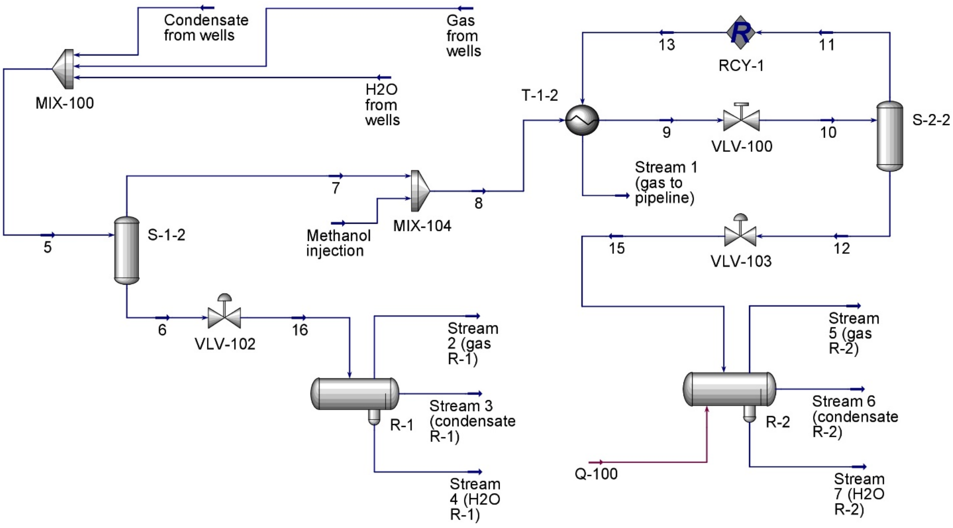


Fig. 1. Scheme of natural gas preparation using the Joule-Thompson effect at the Machukhske field

The scheme in Fig. 1 of gas preparation is usually used at the initial stages of field development, when the wells have high reservoir pressure. Due to throttling (adiabatic expansion), natural gas is cooled to the required temperature and then undergoes appropriate separation from the liquid. Throttling and cooling of the gas below the hydrate formation temperature necessitates the introduction of an inhibitor into the gas stream to protect the process equipment from the formation of hydrate plugs.

To model the gas preparation process using the Joule-Thompson effect, the parameters and characteristics of the low-temperature separation process line at the Machukhske field were taken as a basis.

The amount of gas, gas condensate, and associated formation water was selected in quantities that correspond to standard design values for similar low-temperature gas separation (LTS) units used at gas production facilities in Ukraine:

- gas flow rate – 1 million cubic meters per day;
- gas condensate flow rate – 100 tons per day;
- associated formation water flow rate – 10 tons per day.

The gas composition for process modeling corresponds to the averaged component composition of gas from the Machukhske field wells and is given in Table 1. The operating parameters of the flows of this technological line are given in Table 2.

Table 1

Gas composition of Machukhske field

Gas component	Content, % mol
Methane	92.31
Ethane	3.86
Propane	1.10
N-butane	0.29
Iso-butane	0.16
Neo-pentane	0.01
N-pentane	0.08
Iso-pentane	0.09
N-heptane and higher	0.29
Carbon dioxide	0.12
Nitrogen	1.69

Table 2

Operating parameters of the flows of the technological line of the Machukhske field, which is subject to study

Stream Name	Pressure, MPa	Temperature, °C	Pipeline diameter, mm
Gas from wells	6.0	20	114 × 14
Condensate from wells	6.0	20	114 × 14
H_2O from wells	6.0	20	114 × 14
Line 5	6.0	19.99	219 × 12
Line 6	6.0	19.99	57 × 4
Line 7	6.0	19.99	219 × 12
Line 8	6.0	19.71	219 × 12
Line 9	5.95	–15	219 × 12
Line 10	3.5	–30.11	273 × 8
Line 11	3.5	–30.11	273 × 8
Line 12	3.5	–30.11	57 × 4
Line 13	3.5	–30.11	273 × 8
Line 15	1.4	–36.69	57 × 4
Line 16	3.5	19.10	57 × 4
Methanol injection	6.0	20	12 × 2
Stream 1 (gas to pipeline) – product gas line to main gas pipeline	3.45	10.87	273 × 8
Stream 2 (gas R-1) – degassing gas line from separator P-1	3.5	19.10	57 × 4
Stream 3 (condensate R-1) – condensate line from separator P-1	3.5	19.10	57 × 4
Stream 4 (H_2O R-1) – associated formation water line from separator P-1	3.5	19.10	57 × 4
Stream 5 (gas R-2) –degassing gas line from separator P-2	1.4	20	57 × 4
Stream 6 (condensate R-2) – condensate line from separator P-2	1.4	20	57 × 4
Stream 7 (H_2O R-2) – associated formation water line from separator P-2	1.4	20	57 × 4

A description of the gas preparation process on the Machukhske field technological line and the modeling results are given in the following subsection.

3. Results and Discussion

3.1. Analysis of the technological mode of operation of the Machukhske field gas preparation line

In order to determine the areas where it is advisable to use a microwave radiation device to prevent hydrate formation in industrial pipelines, a computer simulation of the low-temperature gas separation process on one of the Machukhske field technological lines was carried out (Fig. 2).

The products from the wells under a pressure of 6.0 MPa and a temperature of 20°C pass through the inlet separator S-1-2 (separator model – 1200-15.2-1-I, manufactured by LLC "Mashzavod", Chernivtsi), where the droplet liquid is separated from the gas. With the specified thermobaric parameters, there are no conditions for the formation of gas hydrates in gas lines 5 and 7. The temperature of the beginning of hydrate formation in line 5 is +14.35°C, which is lower than the operating temperature, therefore there is no need to use a hydrate formation inhibitor in this section. The temperature of the beginning of hydrate formation in line 7 is +14.37°C, which is lower than the operating temperature, therefore there is no need to use a hydrate formation inhibitor in this section.

Since the gas flow is then directed to the inlet of the heat exchanger pipe space for isobaric cooling to a temperature of −15°C, there is a need to reduce the temperature of the onset of hydrate formation, since the temperature of the onset of hydrate formation in this section is +14.31°C, which is higher than the operating temperature of the gas. That is why the gas flow before entering the pipe space of the heat exchanger T-1-2 (heat exchanger type – "gas-gas", shell-and-pipe, heat exchange area – two sections of 350 m^2, manufactured by ALC "Severodonetsk plant of chemical non-standardized equipment", Severodonetsk, Ukraine) is injected with a methanol hydrate formation inhibitor in the amount of 0.884 t/day. Due to this, the temperature of the onset of hydrate formation in section 9 is reduced to −16.19°C, and accordingly, the conditions for the formation of gas hydrates disappear.

The throttle device VLV-100 (adjustable flange manual throttle, model – NGDR DN200/PN16.0 MPa, manufactured by LLC SPF "STOM", Kharkiv, Ukraine) throttles the gas pressure to a value of 3.5 MPa, due to the Joule-Thompson effect, the gas temperature after the throttle decreases to −30.11°C. Section 10 after the throttle is a zone of active hydrate formation, since the actual temperature of the beginning of hydrate formation at such a pressure is −23.40°C.

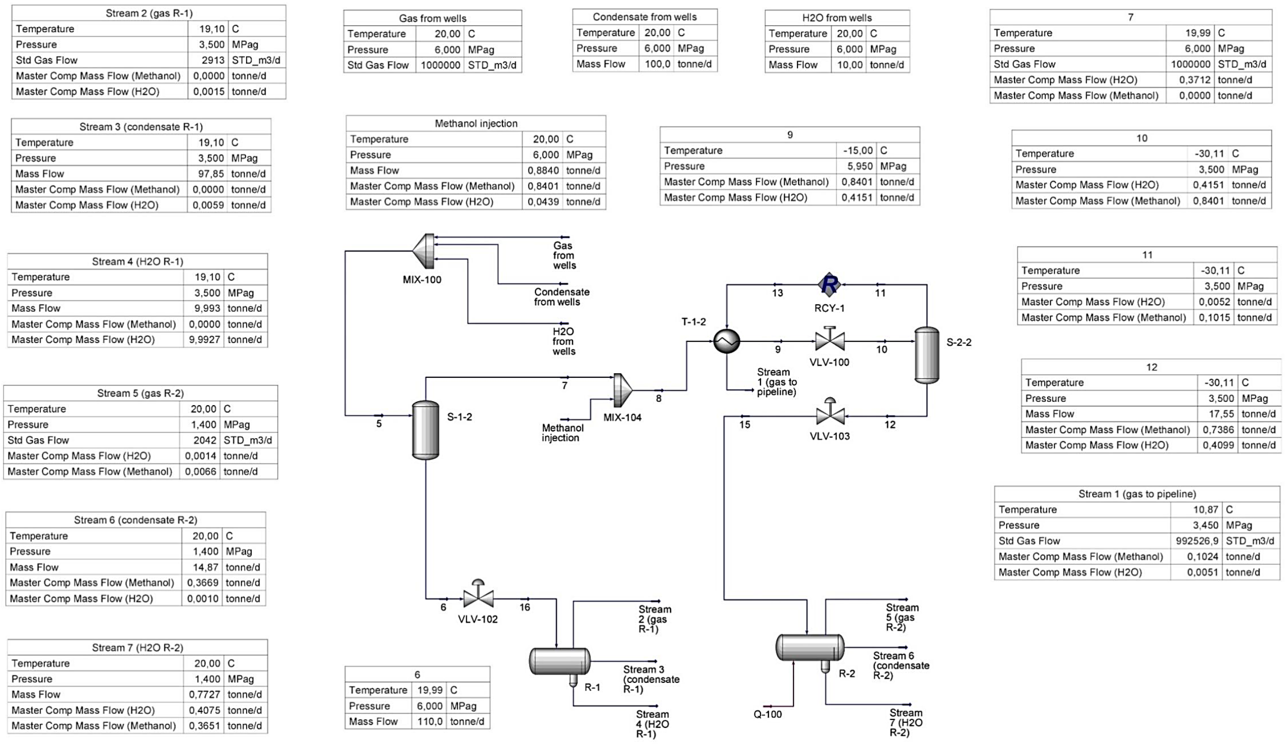
Section 10 from the throttle to the separator S-2-2 (low-temperature vertical gas separator DN 1400, manufactured by ALC "Severodonetsk plant of chemical non-standardized equipment", Severodonetsk, Ukraine) is a steel pipeline with an outer diameter of 273 mm, a wall thickness of 8 mm and a length of 20 meters.

To protect section 10 from hydrate formation, it is necessary to increase the inhibitor consumption by 30%, then the temperature of the onset of hydrate formation in section 10 will be lower than the operating temperature of the gas (Fig. 2).

After the separator C-2-2 in sections 11, 13, as well as in the interpipe space of the heat exchanger T-1-2 and further, the gas transportation process is carried out in a hydrate-free mode. This is due to the significant removal of moisture in the separator C-2-2 due to low-temperature separation and a decrease in the dew point of the gas by moisture below the temperature parameters of the technological process.

In the gas lines venting from the separators P-1 and P-2, the temperatures of the onset of hydrate formation are lower than the operating temperatures of the gas, which is reflected in Table 3, therefore, there is no need for protection against hydrate formation in these sections.

Considering that on the Machukhske field technological line, which is being investigated, the most critical in terms of gas hydrate formation conditions is section 10 between the VLV-100 throttle device and the S-2-2 separator (Fig. 2), and to protect it, it is necessary to ensure a significant excess of the methanol hydrate formation inhibitor (30% more than the nominal value), let's consider it promising to install a microwave emitter to prevent hydrate formation precisely at section 10.



Stream 2 (gas R-1)		
Temperature	19,10	C
Pressure	3,500	MPag
Std Gas Flow	2913	STD_m3/d
Master Comp Mass Flow (Methanol)	0,0000	tonne/d
Master Comp Mass Flow (H2O)	0,0015	tonne/d

Stream 3 (condensate R-1)		
Temperature	19,10	C
Pressure	3,500	MPag
Mass Flow	97,85	tonne/d
Master Comp Mass Flow (Methanol)	0,0000	tonne/d
Master Comp Mass Flow (H2O)	0,0059	tonne/d

Stream 4 (H2O R-1)		
Temperature	19,10	C
Pressure	3,500	MPag
Mass Flow	9,993	tonne/d
Master Comp Mass Flow (Methanol)	0,0000	tonne/d
Master Comp Mass Flow (H2O)	9,9927	tonne/d

Stream 5 (gas R-2)		
Temperature	20,00	C
Pressure	1,400	MPag
Std Gas Flow	2042	STD_m3/d
Master Comp Mass Flow (H2O)	0,0014	tonne/d
Master Comp Mass Flow (Methanol)	0,0066	tonne/d

Stream 6 (condensate R-2)		
Temperature	20,00	C
Pressure	1,400	MPag
Mass Flow	14,87	tonne/d
Master Comp Mass Flow (Methanol)	0,3669	tonne/d
Master Comp Mass Flow (H2O)	0,0010	tonne/d

Stream 7 (H2O R-2)		
Temperature	20,00	C
Pressure	1,400	MPag
Mass Flow	0,7727	tonne/d
Master Comp Mass Flow (H2O)	0,4075	tonne/d
Master Comp Mass Flow (Methanol)	0,3651	tonne/d

Gas from wells		
Temperature	20,00	C
Pressure	6,000	MPag
Std Gas Flow	1000000	STD_m3/d

Condensate from wells		
Temperature	20,00	C
Pressure	6,000	MPag
Mass Flow	100,0	tonne/d

H2O from wells		
Temperature	20,00	C
Pressure	6,000	MPag
Mass Flow	10,00	tonne/d

Methanol injection		
Temperature	20,00	C
Pressure	6,000	MPag
Mass Flow	0,8840	tonne/d
Master Comp Mass Flow (Methanol)	0,8401	tonne/d
Master Comp Mass Flow (H2O)	0,0439	tonne/d

9		
Temperature	-15,00	C
Pressure	5,950	MPag
Master Comp Mass Flow (Methanol)	0,8401	tonne/d
Master Comp Mass Flow (H2O)	0,4151	tonne/d

6		
Temperature	19,99	C
Pressure	6,000	MPag
Mass Flow	110,0	tonne/d

7		
Temperature	19,99	C
Pressure	6,000	MPag
Std Gas Flow	1000000	STD_m3/d
Master Comp Mass Flow (H2O)	0,3712	tonne/d
Master Comp Mass Flow (Methanol)	0,0000	tonne/d

10		
Temperature	-30,11	C
Pressure	3,500	MPag
Master Comp Mass Flow (H2O)	0,4151	tonne/d
Master Comp Mass Flow (Methanol)	0,8401	tonne/d

11		
Temperature	-30,11	C
Pressure	3,500	MPag
Master Comp Mass Flow (H2O)	0,0052	tonne/d
Master Comp Mass Flow (Methanol)	0,1015	tonne/d

12		
Temperature	-30,11	C
Pressure	3,500	MPag
Mass Flow	17,55	tonne/d
Master Comp Mass Flow (Methanol)	0,7386	tonne/d
Master Comp Mass Flow (H2O)	0,4099	tonne/d

Stream 1 (gas to pipeline)		
Temperature	10,87	C
Pressure	3,450	MPag
Std Gas Flow	992526,9	STD_m3/d
Master Comp Mass Flow (Methanol)	0,1024	tonne/d
Master Comp Mass Flow (H2O)	0,0051	tonne/d

Fig. 2. Results of modeling of low-temperature separation using the Joule-Thompson effect at the Machukhske field

Table 3

Results of the study of hydrate formation conditions and methanol hydrate formation inhibitor consumption in the technological lines of low-temperature gas separation units of the Machukhske field

Stream name	The temperature of the beginning of hydrate formation in the gas line, °C	Gas consumption, st. m^3/day	Liquid consumption, t/day	Methanol content, t/day	Water content, t/day
Gas from wells	14.37	1000000	–	0	0.3713
Condensate from wells	–	–	100	0	0
H_2O from wells	–	–	10	0	10
Line 5	14.35	1000000	110	0	10.3713
Line 6	–	–	110	0	10.0001
Line 7	14.37	1000000	0	0	0.3712
Line 8	14.37	1000459	0.0056	0.8401	0.4151
Line 9	14.31 (*–16.19)	996025	8.759	0.8401	0.4151
Line 10	10.36 (*–23.40)	992524	16.62	0.8401	0.4151
Line 11	–30.74	992524	0	0.1015	0.0052
Line 12	–	0	16.62	0.7386	0.4099
Line 13	–30.74	992524	0	0.1015	0.0052
Line 15	–	1213	15.69	0.1015	0.0052
Line 16	–	2913	97.85	0	10.0001
Methanol injection	–	0	0.8840	0.8401	0.0439
Stream 1 (gas to pipeline) – product gas line to the main gas pipeline	–30.74	992524	0	0.1015	0.0052
Stream 2 (gas R-1) – degassing gas line from separator P-1	11.08	2913	0	0	0.0015
Stream 3 (condensate R-1) – condensate line from separator P-1	–	0	97.85	0	0.0059
Stream 4 (H_2O R-1) – associated formation water line from separator P-1	–	0	9.993	0	9.9927
Stream 5 (gas R-2) – degassing gas line from separator R-2	8.63	2042	0	0.0066	0.0014
Stream 6 (condensate R-2) – condensate line from separator R-2	–	0	14.87	0.3669	0.0010
Stream 7 (H_2O R-2) – associated formation water line from separator R-2	–	0	0.7727	0.3651	0.4075
Q-100 – energy for heating the liquid in separator R-2	29.20 kW				

Note: * – the temperature of the onset of hydrate formation in streams 9 and 10 in the case of injection of a hydrate formation inhibitor before the heat exchanger is shown in brackets

3.2. Improving the design of the device for microwave prevention of hydrate formation

The basis for creating a device for microwave prevention of hydrate formation in industrial gas pipelines is the task of reducing the use of environmentally harmful inhibitors (in particular, methanol) by introducing microwave electromagnetic radiation into the gas pipeline. The effect of microwave electromagnetic radiation on gas hydrates is based on the selective absorption of electromagnetic wave energy by water molecules, resulting in heating and dissociation of the gas hydrate structure.

The problem is solved by placing a technological insert with a microwave electromagnetic emitter (magnetron) located on it, the antenna of which is located inside the gas pipeline, approximately in the middle part of the gas pipeline section connecting the throttling valve with the low-temperature separator. Thus, the introduction of microwave electromagnetic radiation into the gas pipeline is achieved. The technological insert with the magnetron installed on it is made removable with welded flanges, which allows for quick maintenance of the equipment.

The structural and technological insert is equipped with a microwave electromagnetic radiator (Galanz M24FB-210A 1000W magnetron, Samsung, manufactured in China). It contains sequentially welded sections of the diffuser (concentric steel transition, manufactured in Ukraine, dimensions are selected depending on the diameter of the gas pipeline), a straight pipeline and a reducer. In the space of these sections there is a fluoroplastic ring with an internal hole (Ftoroplast 150 gasket, manufactured in Turkey), equal to the internal diameter of the gas pipeline. This ring has a special cutout for the radiator antenna. This design avoids damage to the antenna by solid particles of the gas flow moving at high speed. The fluoroplastic ring does not interfere with the passage of microwave radiation. Also, at the end of the gas pipeline, in front of the low-temperature separator, a diaphragm is installed, which serves to reflect electromagnetic radiation, which allows to reduce the required magnetron power. Structurally, this diaphragm is made in the form of seven holes with an internal diameter $D = (0.04...0.05)/f$, m, where f is the frequency of electromagnetic radiation of the magnetron, GHz, which allows to reduce its aerodynamic resistance.

Fig. 3 shows a general view of the gas pipeline section from the throttling valve to the low-temperature separator with a technological insert with a microwave electromagnetic radiator installed on it. In the middle part of the gas pipeline section 1, which connects the throttling valve 2 with the entrance to the low-temperature separator 3, a technological insert 4 is placed with a microwave electromagnetic radiator 5 located on it (Fig. 3). Also, on the gas pipeline section 1 in front of the low-temperature separator 3, a diaphragm 6 is installed to reflect electromagnetic waves.

Fig. 4 shows that the diaphragm for reflecting electromagnetic waves is made in the form of seven holes with an internal diameter $D = (0.04...0.05)/f$, m, which allows to reduce its aerodynamic resistance.

The technological insert 1 (Fig. 5) with the microwave electromagnetic radiator 2 located on it is made removable with welded flanges 9, which allows for quick maintenance of the equipment.

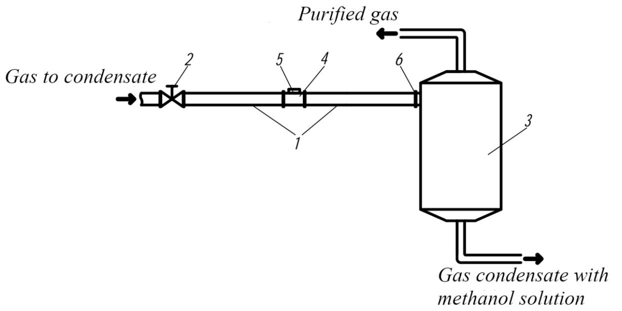


Fig. 3. Structural diagram of a gas pipeline section with a microwave technological insert and a radiation reflection system:
1 – gas pipeline section; 2 – throttling valve; 3 – low-temperature separator; 4 – technological insert; 5 – microwave electromagnetic radiator; 6 – diaphragm (electromagnetic wave reflector)

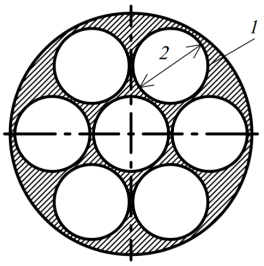


Fig. 4. Front view of the diaphragm for reflecting radiation:
1 – diaphragm hole (in the amount of 7 pcs.); 2 – inner diameter of the diaphragm hole *D*

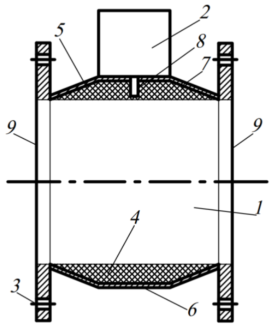


Fig. 5. Structural diagram of a removable technological insert with a microwave emitter mounting assembly and a protective element:
1 – technological insert; 2 – microwave electromagnetic emitter; 3 – mount; 4 – fluoroplastic ring (protective element); 5 – diffuser; 6 – straight section of the pipeline; 7 – reducer; 8 – emitter antenna; 9 – welded flanges

The result of the proposed design solution is reliable protection of the antenna 8 from erosive wear by solid particles of the flow due to its placement in a special cutout of the fluoroplastic ring 4 installed inside the technological insert 1 (Fig. 5). The insert itself, consisting of a sequentially welded diffuser 5, a straight section 6 and a reducer 7, provides stabilization of the hydrodynamic characteristics of the gas medium in the operating zone of the microwave radiator 2 (Fig. 5).

In addition, the placement of the technological insert 4 with the microwave electromagnetic emitter 5 approximately in the middle part of the gas pipeline section 1, which is located between the throttling valve 2 and the low-temperature separator 3, allows to evenly distribute the power of the electromagnetic field along the length of the gas pipeline section 1 (Fig. 3).

Installing the diaphragm 6 in front of the low-temperature separator 3 allows to reflect electromagnetic waves, increasing the power of the electromagnetic field inside the gas pipeline section 1 (Fig. 3). Another place of reflection of electromagnetic waves is the throttling valve 2 (Fig. 3). Such reflection of microwave radiation depends on the length of the gas pipeline section 1 (Fig. 3) and the intensity of absorption of electromagnetic radiation by the internal environment of the gas pipeline (water, ice, gas hydrates) and can occur repeatedly.

In order to reduce aerodynamic resistance, the diaphragm is structurally designed in the form of seven holes with an internal diameter $D = (0.04...0.05)/f$, m (Fig. 4), which ensures reliable reflection of electromagnetic radiation of a microwave electromagnetic emitter operating at a frequency of f, GHz. Due to the geometric optimization of the diaphragm as a reflector and the protection of the antenna with a dielectric fluoroplastic medium, the maximum concentration of electromagnetic energy in the working zone is achieved while maintaining stable hydrodynamics of the gas medium.

For ease of maintenance, the technological insert 4 with the microwave electromagnetic radiator 5 installed on it is made removable, for which two flanges 12 are welded to its ends.

To protect the antenna 8 of the microwave electromagnetic radiator 2, the technological insert 1 consists of sequentially welded sections: a diffuser 5, a straight pipeline 6 and a reducer 7, in the space of which there is a fluoroplastic ring 4 (Fig. 5). The inner hole of the fluoroplastic ring 4 is equal to the inner diameter of the gas pipeline section and has a cutout of the appropriate shape for the antenna 8 of the microwave electromagnetic emitter 2, which allows to avoid damage to the antenna 8 by solid particles of the gas flow (Fig. 5).

Thus, the implementation of the developed design of the gas pipeline section with an integrated microwave technological insert and a system of reflective elements will allow to effectively solve the problem of hydrate formation in the processes of low-temperature gas separation due to the selective absorption of electromagnetic energy by water molecules. The use of a removable insert with an antenna protected by a fluoroplastic ring and a diaphragm with optimized aerodynamic characteristics ensures high reliability of the equipment and stability of the technological flow, creating a real opportunity to significantly reduce the use of toxic inhibitors and reduce the environmental load on the environment.

3.3. Limitations and prospects for the development of the research

It can be noted that for the correct calculation of the destruction of a gas hydrate plug in a gas pipeline using microwave radiation, it is necessary to take into account a number of factors:

- multimode nature of a real pipeline;
- heterogeneity of the dielectric medium;
- temperature dependence of volumetric heat flows in gas hydrate.

For the practical implementation of the obtained results, it is necessary to improve the mathematical model and develop a specialized computer program to perform modeling based on real operational data. It is also important to accurately calculate the power of the emitter and determine the maximum permissible size of hydrate particles that will not pose a threat to the equipment and stable operation of the gas preparation plant. Solving these technical problems is a necessary condition for the transition from laboratory research to industrial operation.

Therefore, further research will be aimed at studying the thermodynamic conditions of gas hydrate decomposition by ultra-high frequency radiation (UHF) inside a steel gas pipeline and establishing the features of gas hydrate decomposition in the pipeline during volumetric heating by UHF radiation. In particular, it is necessary to investigate the possibility of using a multimode mode of electromagnetic radiation transport in steel gas pipelines to increase the "long-range" of emitters.

The prospect of further research is aimed at improving gas preparation technologies under hydrate formation conditions by using microwave energy, which will reduce methanol consumption to ensure a hydrate-free process and minimize inhibitor ingress into the main gas pipeline and liquid hydrocarbon collection systems

4. Conclusions

1. Using computer modeling in the Aspen HYSYS environment, it was determined that the most critical zone of active hydrate formation on the Machukhske field technological line is section 10 between the VLV-100 throttle device and the S-2-2 separator. It was established that in this zone the actual gas temperature after throttling drops to –30.11°C, while the temperature of the onset of hydrate formation is –23.40°C. Without additional energy input, this requires an excess of methanol consumption of 30% above the nominal value.

2. The device for microwave prevention of hydrate formation in low-temperature gas separation systems has been improved by developing a removable technological insert that integrates a magnetron with a protected antenna and a system of reflective elements. The design solution using a fluoroplastic ring protects the emitter from erosive wear, and the installation of a diaphragm with a hole diameter of $D = (0.04...0.05)/f$ ensures wave reflection and maximum energy concentration in the working zone. This allows for effective destruction of hydrate structures, complete or partial abandonment of the supply of toxic inhibitors, and ensure the environmental friendliness of the technological process.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or other nature that could affect the research and its results presented in this article.

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Data availability

Data cannot be provided for reasons stated in the data availability statement.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the presented work.

Authors' contributions

Taras Podoliak: Software, Formal analysis, Writing – original draft, Writing – review and editing, Visualization; ***Viktoriia Dmytrenko***: Conceptualization, Methodology, Investigation.

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