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ANALYSIS OF THE INFLUENCE OF THE HYDRATE-BEARING ROCKS PROPERTIES ON THE PROSPECTS THEIR INDUSTRIAL DEVELOPMENT

Along with renewable energy and hydrogen, gas hydrates may become the most significant energy resource in the coming years. The reserves of gas in the hydrate state exceed all the combined world reserves of traditional energy resources. At the same time, the gas hydrates properties in the conditions their natural occurrence in the composition of hydrate-containing rock cause significant difficulties in their extraction. In this regard, the industrial use of colossal renewable gas resources in the gas hydrate state is just beginning. Based on this, the methods of developing gas hydrate deposits are the object of research. Based on the analysis and generalization of the currently known examples results of experimental and industrial development of gas hydrate deposits, as well as the results of studying the hydrate-bearing rocks properties, an assessment of the prospects for the industrial implementation of gas hydrate deposit development methods is given. Extraction of methane from gas hydrate deposits causes difficulties due to their solid form. Existing promising methods of their development involve the dissociation of gas hydrate into gas and water.

Currently implemented research and industrial development projects of gas hydrate deposits have shown a number of problems related, first of all, to the instability of the hydrate-bearing rock after dissociation of the gas hydrate (at the same time, in the vast majority, the natural gas hydrate becomes metastable and weakly cemented). Therefore, there is still no commercially attractive technology for obtaining natural gas from gas hydrate deposits. At the same time, the depressurization method is considered the most promising. Based on this, the improvement of the technology of influence on the hydrate-bearing rock for the natural gas extraction should concern the provision of the rock removal the into the well. At the same time, effective and competitive development of marine gas hydrates deposits can be realized only if taking into account the geological features of the distribution of hydrate-bearing rocks, as well as the gas hydrates properties in their natural occurrence.

Keywords: *gas hydrate, hydrate-bearing rock, gas hydrate deposits development, destruction of hydrate-bearing rock, gas extraction.*

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1. Introduction

As experts have repeatedly noted, the XXI century in the global energy aspect should be the «century of gas» [1]. According to the calculations of the US Department of Energy, in 2030, compared to 2003, the value of gas as an energy carrier in the world industry will increase 10 times. After recent developments in the energy sector, as well as the amazing jump in US gas production thanks to shale gas [2], this is not in doubt. A similar situation is observed with methane from coal layers. Even twenty years ago, it was considered that its extraction is technically difficult and unprofitable. Now, due to the development of oil and gas science and the creation of the latest gas production technologies, about 45 billion m^3 is produced annually in the USA alone from more than 10,000 wells.

This rapid growth of the gas role in world consumption, which was unforeseeable even 20–30 years ago, is due to a fundamental change in concepts about the hydrocarbon and gas potential of the earth's subsoil. In addition, in the last 10 years, there has been an exponential increase in the estimation of the world's explored reserves and forecast resources.

The main production comes from traditional free gas fields. At the same time, the role of non-traditional (non-conventional) sources of hydrocarbons is rapidly growing in the structure of world consumption – primarily gas, which includes shale gas, central basin gas, and coal gas. In recent years, they began to be intensively extracted in North America, due to which in 2004–2010 the USA overtook Russia and took first place in the world in gas production.

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As it is known, natural gas capacity is represented by several genetic and, accordingly, industrial-geological and technological-mining types. The first includes deposits of traditional free gas deposits in the state of a solid phase in terrigenous, carbonate, and other reservoir rocks. The second is gas dispersed and occluded in dense rocks of different lithologies with micro- and nano-permeability (shale gas, central basin gas, coalbed methane). The third type is represented by methane dissolved in underground waters, and the fourth by methane, which is in deposits as a gas hydrate [3].

Along with renewable energy and hydrogen, gas hydrates may become the most significant alternative energy resources in the coming years. According to the estimates of modern researches, it is known that reserves of gas in the hydrate state amount to about $1.5 \cdot 10^{16}$ m^3 [4]. These estimates exceed all combined world reserves of conventional energy resources.

At the same time, the gas hydrates properties in the conditions their natural occurrence in the composition of hydrate-containing rock cause significant difficulties in their extraction. In this regard, the industrial use of colossal renewable gas resources in the gas hydrate state is just beginning. At the same time, taking into account the experience of shale gas development on the North American continent, in the near future it is possible to expect amazing «jumps» in gas production associated with gas hydrate deposits. This applies, for example, to Japan (14 gas hydrate deposits have been discovered in its waters [5]).

Therefore, the development of gas hydrate deposits is an innovative and extremely promising technological direction of the mining industry development. At the same time, the extracted gas can become one of the main sources of energy hydrocarbon resources in the world. However, effective and competitive development of marine gas hydrates deposits can be implemented only if the geological features of the hydrate-bearing rocks distribution, as well as the gas hydrates properties in their natural occurrence, are taken into account. Therefore, it is precisely on this basis that the assessment of the prospects for the development of gas hydrate technologies should be based. Based on this, *the object of research* is the methods of developing gas hydrate deposits. *The aim of research* is to assess the prospects for industrial implementation of existing methods of developing gas hydrate deposits on the basis of taking into account the geological features their occurrence and the characteristics of hydrate-bearing sedimentary rocks.

2. Research methodology

The assessment of prospects for the industrial implementation of gas hydrate deposit development methods was carried out based on the analysis and generalization of the currently known examples results of experimental and industrial gas hydrate deposits development, as well as the results of studying the properties of hydrate-bearing rocks.

3. Research results and discussion

The prospects of methane gas hydrates arouse the interest in this topic of a number of scientific schools and companies that are positioned in the sector of energy mineral extraction in France, Germany, the USA, Canada, India, Japan, etc. [6, 7]. Currently, more than 30 countries are conducting active research and research and industrial exploitation of gas hydrates. Many countries have developed long-term strategies for the development of gas hydrates and large national projects, provided for the financing of gas hydrate projects, their experimental operation and relevant technical research from the state budget. Some countries, such as the USA, Japan, Canada, and China, have drawn up their own schedule for the commercial development of gas hydrate deposits [8].

At the same time, it should be emphasized that the main stratigraphic, structural-tectonic, depth, phase-geochemical ranges of oil and gas capacity of the territory of Ukraine fully correspond to the global laws of oil and gas accumulation [1]. The existence of all genetic and, accordingly, industrial types of natural gas has been proven in the Ukrainian underground. Along with free, all potential sources of non-conventional (shale, central basin, coal), alternative (water dissolved, gas hydrate) gas are established here [3]. Therefore, one can agree with Academician E. F. Shnyukov and professor of the Texas University Yu. F. Makogon, that in the future, Ukraine can completely supply itself with gas from the Black Sea gas hydrates themselves [3].

Back in 2000, the Law of Ukraine «On Alternative Types of Liquid and Gas Fuel» was adopted, which defined «the legal, social, economic, ecological and organizational principles of production (extraction) and consumption of alternative types of liquid and gas fuel based on the involvement of non-traditional sources and types of energy raw materials» [9].

In [10], it was concluded that the zone of conditions favorable for hydrate formation processes in the Black Sea begins at depths of 700–750 m. The thickness of this zone is estimated from 500 to 1000–1200 m. Taking into account the data of seismic exploration, an estimate of the forecast methane reserves in the Black Sea gas hydrate deposits was given – 25–30 trillion m^3 only for the deep-water part of the sea.

According to [11], gas hydrate methane resources in the Ukrainian sector of the Black Sea amount to almost 7 trillion m^3. At the same time, intensive restoration of unconventional natural gas resources was also recorded. This applies to methane dissolved in underground waters (its resources in the oil and gas basins of Ukraine are practically inexhaustible) and methane gas hydrates of the Black Sea, the bottom of which has an abnormally high intensity of gas generation [3].

Natural gas is concentrated on the planet in various types and forms. Gas hydrates or methane hydrates are one of the forms of existence of hydrocarbons in nature. It appears when methane forms an unstable compound with water at a certain combination of temperature and pressure. About 98 % of gas hydrate deposits are concentrated on the shelf and continental slope of the World Ocean at a depth of 200 to 700 meters [12].

Currently, more than 250 gas hydrate deposits have been discovered in the world [13]. They were found near the coasts of the USA, Canada, Costa Rica, Mexico, India, Japan and China, as well as in the Mediterranean, Black and Caspian seas. Therefore, practically every country with access to the ocean has the opportunity to participate in the development of colossal gas deposits in the composition of gas hydrates. As a result, the technology for the development of gas hydrate deposits, implemented on an industrial scale, is capable of reformatting the entire gas market.

Gigantic deposits of methane gas in hydrate form have been found in marine sediments of continental slopes and permafrost areas (coastal and marine permafrost) all over the globe [12]. One of the most famous gas hydrate accumulations in the world at the moment are the Malik (Canada) and Nankai (Japan) deposits. Based on calculated data, it is known that the first field contains about 110 billion m^3 of gas, and the second – up to 60 trillion m^3 of gas [14].

In the deep-water coast of West Africa, monomineralic, without terrigenous material admixtures, gas hydrate bodies were found in the cavities of faults and cracks. When drilling gas hydrate wells in the western part of the Nankai Trough near the Japanese island of Honshu, multi-meter cores were raised, where layers of monomineralic massive gas hydrate several centimeters thick were also observed among the siltstones. Larger interlayer bodies of monomineral hydrate are also known. One of them, lenticular and the largest in the world was discovered by well No. 84 of the Deep Sea Drilling Project. Having a thickness of about 4–5 m, it contains only 5–7 % of non-hydrated, detrital material and lies in a 15-meter aquifer, the sole of which is located 240–255 m below the bottom of a deep-sea trough on the continental slope near Guatemala. A 9-meter core of hydrate-cemented volcanic ash was raised from another well drilled off the coast of Costa Rica. The pore space of the core, which was 62 %, was filled with hydrate. This hydrate-bearing formation has an average thickness of 236 m. Its average porosity is 60.1 % [6].

During the investigation of the NGHP-01-10 well, a thick interval of fractured clays was found, the hydrate content of which is one of the highest in the world [15]. Hydrate-saturated rocks mined from the Indian deep water area of the Krishna Godavari are represented by massive fractured shales (Fig. 1), and the technology of their extraction must be significantly different from the existing ones today.

Fig. 1. Gas hydrate in fractured shales of the deep-water part of the Krishna Godavari basin, India [15]

Marine gas hydrate reservoirs are typically found in shallow, loose, soft, unconsolidated sediments less than 400 m below the seafloor, where water depths exceed 800 m and sand is a minor fraction. Water-saturated sediments are mostly clayey silt with very small grain sizes and thus have low permeability, which is mostly less than a few mD [16]. Thermobaric conditions of hydrate accumulation zones maintain gas hydrate in a stable state. However, it does not have a high-quality roof and a stable reservoir, like traditional oil and gas fields, and the hydrate itself is the skeleton of the formation. It is a kind of metastable and weakly cemented hydrate. When the thermobaric conditions at the bottom of the sea change under the influence of geological processes or as a result of technogenic influence during its operation, this type of metastable hydrate can decompose in large quantities, the reservoir can collapse, and uncontrolled gas dispersion can occur. Therefore, it is very important to rationally and safely develop gas hydrate in deposits of this type. This creates engineering challenges, including the need to ensure wellhead and wellbore stability and control rock drift.

From the point of view of the possible production of gas from deposits of natural gas hydrates, its deposits in coarse sands are landmarks, since the porosity and permeability of coarse sands are high [17].

For example, a significant amount of natural gas hydrates was found in coarse-grained, fine-grained and fractured reservoirs. Examples of such reservoirs are sandy deposits near the margins of the deep ocean in the area of Japan [18], sediments on the continental slopes of the Gulf of Mexico [19], and turbidite sands in the Ulleung Basin off the coast of Korea [20].

However, it is assumed that less than 10 % of all natural gas hydrates accumulate in coarse sands [21].

Extraction of methane from gas hydrate deposits causes difficulties due to their solid form. Existing promising methods of their development involve the dissociation of gas hydrate into gas and water. There are four ways of extracting gas from gas hydrate deposits that can be implemented on an industrial scale (thermal, depressurization, introduction of chemical reagents and replacement of methane with carbon dioxide). Of these methods, two are currently recognized as having prospects for industrial implementation. These are thermal (presupposes an increase in reservoir temperature) and depressurization (presupposes a decrease in pressure in the production zone). At the same time, the depressurization method is considered the most promising. Mining equipment for the implementation of these technologies is located on the seabed. Further processes of extracted gas preparation are carried out in accordance with existing technologies [22].

However, it should be noted that there is still no commercially attractive technology for obtaining natural gas from gas hydrate deposits.

The method of thermal stimulation involves heating the hydrate-bearing rock with a coolant (steam heated by water) to dissociate the gas hydrate into gas and water [23]. For example, thermal stimulation was carried out during an industrial test at the Mallick field in Canada. However, it showed extremely low productivity – only 470 m^3 of gas was produced in 5 days [24].

The depressurization method is implemented by lowering the pressure in the productive reservoir below the level of gas hydrate stability. This causes its dissociation. At the same time, this method does not require constant stimulation and is considered the most economical with a significant potential for industrial implementation [25]. However, it should be taken into account that a decrease in pressure in the formation leads to a decrease in its temperature (according to the Joule-Thomson effect) and the threat of the man-made gas hydrate formation in the blowout zone. This can induce related complications and decrease the productivity of the well [24]. This method was tested during the implementation of experimental and industrial development of a deposit of gas hydrates in 2013 in the area of the Nankai depression near Japan [26].

When applying the well depressurization method for gas hydrate dissociation in hydrate-bearing rock, a change in temperature fields and pressure is observed in it. As a result, the gas hydrate dissociates intensively, the structure of the formation is destroyed and an uncontrolled leakage of a significant amount of gas is possible [16]. This is confirmed by the fact that experiments on gas hydrate production in recent years have been stopped directly or indirectly due to sand mining [27]. As confirmation, it is possible to cite the results of research and industrial development of a gas hydrate deposit in the area of the Nankai Trough near the coast of Japan in 2013 [28]. The method of deposit depressurization in the process of liquid pumping was applied. Production lasted 6 days with a total gas production of $1.2 \cdot 10^5$ m^3 (average daily production was $2 \cdot 10^4$ m^3). The productive layer with a capacity of 60 m is located 270 m below the level of the seabed, the depth of which in this place is about 1000 m.

A significant problem was the fact that methane release as a result of gas hydrate dissociation was accompanied by cooling of the adjacent hydrate-bearing rock and, first of all, of the hydrate itself. As a result, its stability increased, and the melting intensity, accordingly, decreased. To maintain the planned production level, the pressure at the wellhead was gradually reduced. It was planned to bring it to 3 MPa in 14 days. However, already on the sixth day of mining, when the pressure at the mouth was 4.5 MPa, intensive removal of the rock took place. Mining had to be stopped to solve this problem. At the same time, of course, the well was equipped with a sand trapping system. However, the intensity of the process was much higher than expected.

In 2017, two stages of new industrial tests with two types of sand protection structures were conducted in this area [29]. The first operation lasted 12 days and was stopped again due to sand mining. At the same time, gas production was $3.5 \cdot 10^4$ m^3, which is significantly less (only 1/7) than the previous test in 2013. The second operation was reportedly halted due to poor weather conditions with 24 days of continuous production. At the same time, about $2.0 \cdot 10^5$ m^3 ($8.33 \cdot 10^3$ m^3/day) of gas was produced, which is still far from optimal.

Similar problems were noted in the course of other projects of research and industrial development of gas hydrates. Therefore, the use of the depression method for the extraction of non-diagenetic gas hydrate will be accompanied by the following risks:

– stoppage of production due to clogging of the well with silt and sand;
– a significant amount of released gas can disperse in the marine environment, which can lead to irrational consumption of resources, low gas production rate and low productivity;
– during long-term operation, the hydrate layer will collapse, which can lead to instability of the rock massif, underwater landslide, etc.;
– deformation of the structure of the seabed can lead to instability and loss of control over industrial equipment, which leads to a decrease in production safety;
– a significant amount of scattered gas can threaten the safety of shipping and harm the marine ecology;
– the gas, in the case of entering the atmosphere, will create a greenhouse effect.

Common to any possible method of obtaining methane from gas hydrate is the need to transfer the appropriate amount of thermal energy to it. For example, up to 12 % is spent on hydrate dissociation in terms of extracted gas. In the depressurization method, as a rule, it is assumed that it comes from the rock layers surrounding the reservoir. However, the possibility and power of receiving a sufficient amount of heat from the surrounding layers to ensure sufficient performance of the technology based on pressure reduction has not yet been proven.

However, in general, positive results have been obtained in the process of experimental and industrial tests conducted so far using the depressurization method. So, for example, in 2002, tests were conducted on gas extraction by pressure reduction at the Mallik field in the Mackenzie Delta. Three wells were drilled to a depth of 1168 m, one parametric and two observation wells. The gas flow was over 285,000 m^3/day [14].

4. Conclusions

Today, there is considerable interest in the colossal resources of natural gas in the composition of gas hydrates. However, as a result of the analysis of the principles of implementation of the existing methods of gas hydrate deposits development (depressurization, thermal impact, replacement of CO_2, introduction of chemical reagents) it was established that they are based on the principles of classical gas and oil production technologies. In addition, according to the analysis of currently implemented research and industrial development gas hydrates projects, all them were accompanied by intensive removal of rock. Based on the fact that this complication was recorded during a short-term test mining, it can be predicted that this problem will be the main obstacle to the implementation of a long-term technological process. At the same time, from a geological point of view, these tests were carried out in productive layers composed of the most fracture-resistant hydrate-bearing rocks.

Thus, the use of classical approaches in the implementation of technology for the development of gas hydrate deposits will fundamentally fail to guarantee a continuous high-performance process. Therefore, the urgent task of further research in this direction is the development of an innovative method of developing gas hydrate deposits based on the maximum consideration of the properties of hydrate-bearing rocks within the likely range of thermobaric parameters.

In addition, taking into account the features of occurrence and hydrate-bearing rocks properties determines the sequence of their development. So, for example, about 90 % of gas hydrate resources are concentrated in non-diagenic deposits. However, due to the inevitable destruction of the hydrate skeleton, the entire volume of such rocks around the well during development will turn into an uncontrolled moving mass. This will make the process of gas extraction impossible. At the same time, taking into account the positive experience of research and industrial development projects using the depressurization method, in this technology it is expedient to foresee the dissociation of gas hydrate as a result of the creation of a depression and the arrival of thermal energy from the surrounding rocks.

These conclusions should also be taken into account when specifying the strategy for the implementation of scientific and technical projects (developments) of research institutions and energy companies of Ukraine.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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