Research of the possibilities of the existing transport system in Russia for the transportation of goods and methane-hydrogen mixtures for export

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Abstract. The theory of using hydrogen and hydrogen-methane mixtures (HMC) assumes the operation of an industrial cluster created in the presence of significant reserves of methane, excess electricity, trunk pipeline facilities for transportation and storage, as well as contracts for the supply of mixtures to the domestic market and export. For a balanced decision on the use of existing facilities of the gas transmission network and underground storage facilities for methane-hydrogen mixtures, determination of transit volumes, additional research is required in order to take into account the peculiarities of the behaviour of hydrogen and its mixtures. The authors carried out work to systematize the features of production and storage, assess the consequences of accompanying negative effects to maintain the operational reliability of the production complex. Taking into account the preliminary results, additional research and the adoption of national and industry standards are required before starting significant investments in the creation of a hydrogen energy industry.

1. Introduction
An analysis of the possibilities of using the infrastructure and facilities of the existing storage and transportation system for hydrogen and hydrogen-methane mixtures should be carried out, considering the UGSS complex as a unique production and technological complex, taking into account the specifics of its facilities, technological, economic, social, environmental and market requirements. The reliability of supply to consumers is determined by the reliability of the UGSS functioning as a whole (the availability of production, the stability of supplies through the main transport and gas distribution systems, the availability, location and production capacities and capabilities of UGS facilities).

Pursuing a policy of "diversification" of energy supply sources, the leadership of the United Europe actively supports the introduction of renewable energy sources, including the production of "green gas", which includes biogas, synthetic methane, and hydrogen.

Transportation of hydrogen and hydrogen-methane mixtures (HMC) through main gas pipelines, as well as accumulation and storage in existing underground gas storage facilities (UGS) of the incoming facilities of the Unified Gas Supply System of Russia (UGSS) in these conditions is a prerequisite for the development of a "carbon-neutral" strategy of the country for the development of both domestic consumption and the organization of export supplies of raw materials to European countries.

This approach is economically justified due to the idea of accumulating and storing significant industrial volumes of hydrogen in facilities previously intended for the supply of natural gas (methane), which reduces the need for huge investments in infrastructure development, involves the...
use of personnel competencies, specializations of organizations, as well as the preservation of technologies and objects [1].

Operational experience and scientific studies have shown that the joint storage of methane with hydrogen has a number of serious differences associated with predicting changes in the stress-strain state of reservoirs, hydrochemical and microbiological conditions in underground storage facilities, as well as the properties of infrastructure facilities, which implies a number of scientific studies, and taking measures to reduce negative man-made and mechanical consequences within the framework of the operation of facilities. An effective option for taking into account the specifics of working with hydrogen is the organization of an on-line flow control of the quality of gas mixtures, which ensures the safety of the technological process due to the prompt acquisition of data, which makes it possible to take technological and managerial decisions in advance in order to reduce risks, optimize and reduce costs during operation. It is advisable to organize these works and take into account when creating national and industry standards for the design and operation of UGSS infrastructure facilities before the start of significant investments related to the behavior of hydrogen and hybrid mixtures during their transportation and storage.

2. Problems of hybrid storage of hydrogen-methane mixtures
Hydrogen is an integral component of natural organic compounds and under natural conditions is the lightest, most mobile and reactive gas, but the multiphase storage properties in porous media remain uncertain and unexplored. Since hydrogen gas is composed of small and light molecules, it has a strong ability to migrate in a porous medium and can be highly reactive with rock-forming minerals. Due to different geological conditions, additional studies of the UGS enclosing rocks will expand the understanding of the potential interaction of organic and inorganic components and their impact on reservoir quality during all technological cycles in natural storage facilities [2]. Hydrogen injection into porous reservoirs is capable of displacing formation fluids, which will lead to complex multiphase crossflows. Hydrogen storage operations must be based on accurate prediction of multiphase fluid movement in porous media. In fact, the redox reactions induced by hydrogen can change the mineral association of the rock.

The density of hydrogen increases with increasing pressure, which leads to an increase in hydrogen storage efficiency with depth. The low hydrogen density compared to formation brines leads to buoyancy, which promotes the formation of a hydrogen cap directly under the seal. The viscosity of hydrogen is low compared to methane and carbon dioxide and exhibits minimal fluctuations in pressure and temperature over the range of typical subsurface storage conditions (T <150 ° C; P <50 MPa). Hydrogen also has a relatively high thermal conductivity, which increases with increasing pressure and temperature, so that in deep storage horizons, this indicator for hydrogen is almost three times higher than for methane and carbon dioxide.

As with other gases, the solubility of hydrogen in water increases with increasing pressure and decreases with increasing temperature and increasing salinity. Of particular importance are relative permeability, capillary pressure and residual hydrogen saturation in water-saturated porous media, which are directly related to the phases present within the formation. Determination of residual hydrogen saturation controls the irrecoverable part of the stored gas, affecting the economic viability. In turn, the capillary forces governing the residual entrapment also govern the rock absorption and drainage behavior, and hence the relative permeability. It should be noted that the relative permeability can change over time as a result of multiple cycles of injection and production of hydrogen. In the case of accumulation of hydrogen in the sedimentary strata, changes in the porous structure of the rock occur, which affects the capacity of underground gas storages. In addition to abiotic reactions, microbial activity is manifested in the conditions of underground storage of hydrogen.

The capacities of the storage facilities allow, during the period of maximum consumption (heating period), to provide in a short time from 20 to 40% of the needs of all produced gas and to ensure storage and injection in a reverse mode. Determination of the sealing properties of the cover rock and the wellbore zone is important for site selection and operating conditions. For example, in salt caverns,
as practice shows, the operating gas pressure range should be from 24% to 80% of the overburden pressure. The upper limit of the working pressure is set in order to avoid the formation of cracks, and the lower one is determined based on the preservation of the injectivity of the reservoir. In porous reservoirs, proper flow rate is a vital parameter to avoid aquifer brine entering the perforated area of the well. The behavior of hydrogen stored in natural storage facilities is a multi-criteria process that requires systematization and ranking of possible risks.

3. Manifestation of corrosion in the process of storing hybrid gas mixtures

Due to the fact that the objects of the gas transmission system are classified as hazardous, industrial facilities accidents at them are fraught with injuries and loss of life, destruction of residential and industrial buildings, failure of contractual obligations and, in all cases, causing significant material damage to enterprises. Taking this into account, in order to ensure the level of acceptable risks, it is necessary to analyze both the significance of the damage and the likelihood of adverse events. The reliability indicators of pipes and equipment of the gas transmission system are assessed in the process of developing a project for a construction and/or a gas supply facility in relation to specific design and operation conditions [2-4].

The assessment of the reliability indicator is the numerical value of the indicator determined in one way or another. Reliability indicators are evaluated: 1) on statistical data on failures, 2) on the basis of accumulated engineering experience (by expert way), 3) according to the manufacturer and the current requirements for the reliability of equipment, 4) joint use of statistical and expert approaches, 5) by joint analysis of the density of load distribution and the density of distribution of limit voltages (according to the theory of structural reliability and is intended to assess the integrity of vessels, under internal pressure).

When assessing reliability indicators, it is recommended to use the following sources of information: 1) industry databases on the accident rate of gas supply system facilities, 2) regulatory and reference data, 3) scientific and technical literature, 4) research reports, 5) operational data of production enterprises of the industry, 6) data of manufacturers on the forecast values of equipment reliability indicators, 7) international, state and industry standards of developed countries (for example: ISO TS 29001 Petroleum, petrochemical and natural gas industries). Sector-specific quality management systems. Requirements for product and service supply organizations, 8) foreign data on the functioning and failures of similar facilities to compare the results [GOST R ISO 20815-2013 "Oil, petrochemical and gas industry. Management of production efficiency and reliability", standards of the Norwegian Petroleum Institute, standards of the American Petroleum Institute, standard of the Norwegian Society for Standardization, etc. relevant to the topic of research].

When forecasting reliability indicators, retrospective information should be combined with qualitative assessments of trends in change and modern engineering experience (expert methods). To correctly interpret the results of the risk assessment, it is necessary to understand the nature of the uncertainties and their causes. Sources of uncertainty should be identified and their impact on results evaluated. Since there are many uncertainties associated with risk assessment for the use of changes in the hydrogen transportation product and its mixture projected for the supply of natural gas, as a rule, the main sources of uncertainty are incomplete information on the reliability of equipment, the failure rate due to the "human factor", as well as assumptions and assumptions and assumptions accepted in the used models for the development of the emergency process. When designing and repurposing the purpose of the main gas pipeline, its system reliability should be determined, reflecting the impact of the gas pipeline used on the reliability of the entire Unified Gas Supply System.

Hydrogen has the ability to water structural materials, resulting in a significantly reduced mechanical properties of steel. Reservoir waters, which are strong electrolytes, intensify the process of hydrogenation.

Operations for the storage of hydrogen together with methane in underground conditions should be predicted considering the understanding of the possibility of man-made changes in the mechanical
properties and stress-strain state of the reservoir, available in the storage of hydro chemical and microbiological conditions, restrictions for multiphase movement of fluids in porous media.

The already identified consequences of the interaction of hydrogen, methane, reservoir waters and microbiological populations are a decrease in the volume of stored gas, the appearance and loss of sulfur structures on engineering structures and networks, the manifestation of hydrogen sulfide, corrosion of equipment and the presence of hydrogen embrittlement of metals for storage facilities and transport infrastructure of the UGSS system.

Unfortunately, the hydrogen content in natural gas significantly impairs the energy parameters and calorific value of natural gas. These criteria must be considered before the transfer of methane-hydrogen mixtures through the pipeline network begins. The pumping of hydrogen-containing gas into existing UGS affects the efficiency of their work, the geological integrity of the formation and overburden rocks, as well as the durability of metal structures.

With the participation of hydrogen, redox reactions can contribute to a change in the capacitive filtration properties of rocks and adversely affect the gas-bearing layer, which causes a deterioration in the permeability of the productive reservoir and reduces the strength of the reservoir rocks up to their destruction. The presence of impurities can lead to changes, complex technical and operational problems such as toxicity, safety and compression or dehydration requirements, since the thermophysical properties of hydrogenic MVS can differ significantly from pure hydrogen flow. The intake of molecular hydrogen changes the rate of microbial biochemical processes [5].

The main features and possible risks in the storage of gas mixtures during hybrid storage are shown in Figure 1.

![Figure 1. Features and possible risks when storing gas mixtures.](image-url)

In addition to problems with raw materials to produce hydrogen and problems with its transportation and storage, it is noted that the use of H₂ as a fuel can also exacerbate the problem of global warming. The essence of the problem is that hydrogen, getting into the atmosphere, reduces the
concentration of hydroxyl radicals in it - powerful oxidants that neutralize harmful products of human life, including greenhouse gases, which purify the air.

Currently, specialists of the OGRI RAS are working to determine the composition and potential functional activity of microbial communities of reservoir water of underground gas storage facilities in aquifers of various depths, to study the behavior of methane-hydrogen mixtures for loose and consolidated porous media.

4. Problems of transportation of hybrid methane-hydrogen mixtures

Currently, the oil and gas industry has established the opinion that the main danger in the transportation of hybrid methane-hydrogen mixtures from gas storage facilities is not to increase the corrosion rate of the metal surfaces involved, but to strengthen the process of watering steel, leading to embrittlement and corrosion cracking of the metal. The reason for the process is the cathode polarization of metal equipment, and the danger of this process is that structures that are in contact with hydrogen-containing media during operation are at risk of a sharp decrease in strength and fragile destruction of equipment under high pressure during transportation and storage. Polarization becomes possible because of various processes:

- Self-dissoluble (corrosion, chemical etching);
- Electrochemical treatment with current imposition (electroplating, cathodic degreasing, electrical protection of surfaces and equipment).

Fundamentally, the hydrogenation of equipment consists of the stages of adsorption, absorption and diffusion of hydrogen and becomes possible not only due to corrosion, but also because of the action of cathodic corrosion protection, which is used for almost all main gas pipelines during operation.

It has been established that corrosion and hydrogen embrittlement of pump-compressor equipment and the pipe part of gas-oil pipelines, field equipment proceed very intensively in the presence of moisture according to the mechanism of electrochemical corrosion.

With the timely detection of corrosion damage, the choice of protective measures to protect the equipment from negative processes is carried out. To reduce adverse effects, regulations and standards are being developed to extend the overhaul periods of equipment and ensure the safety of operation, including:

- application of special corrosion-resistant steels for wells, underground and surface equipment, infrastructure of gas collector networks and pipelines;
- constant dosing (injection) of various inhibitors depending on the conditions;
- application of protective coatings for pre-treatment of equipment.

Taking into account the creation of a separate hydrogen industry, the existing experience should be consolidated and applied in the form of state or industry standards and regulations. With this in mind, the main risks that need to be taken into account for the design and operation of storage and transportation facilities include:

- diffusion and moisture content of the medium transported in pipelines; high activity and reactivity;
- growth of microorganisms that consume hydrogen, the possibility of loss as a result of bacteriological biodegradation and dissolution;
- risk of depressurization; change of the stress field of rock structures during storage;
- the process of embrittlement of engineering structures from metal equipment and plastic structures in the process of storage, transportation and processing;
- carbon dioxide and sulfate corrosion, which is manifested when sulfur and carbonate deposits fall on engineering structures.

In the open literature, several options for the possibility of transporting hydrogen are considered:

- on the existing gas transmission system without restrictions;
- on specially built main pipelines;
- on the existing transport system in sequential pumping mode.
Each of the options has its advantages and disadvantages in terms of reliability and profit in the medium and long term [6-7].

Reducing the volumetric caloric content of hydrogen will lead to an increase in the capacity of the compressor station, provided that the energy power of the flow during transportation is preserved. Estimated transportation indicators show that when transporting hydrogen through pipes at a pressure of 6.5 MPa, about 1% of the transmitted energy is characterized by losses per 1000 km, while the unit costs of transport will be 1.5 times higher than for natural gas. In the case of transportation of mixtures, their indicators should be determined based on the calorific values of the components that make up the composition. An important indicator is the combustion parameter of 1 m3 methane, when 4 times more oxygen is consumed than during the combustion of hydrogen.

Considering the possible risks of transporting hydrogen with methane through the existing gas transportation system, specialists engaged in hydrogen topics identified three possible levels of hydrogen concentration in the mixture for transportation: 1) permissible, non-critical mixing; 2) mixing, requiring the permission of the regulator and control of processes; 3) mixing, the possibility of which requires further study and has significant risks.

The widespread use of methane-hydrogen mixtures will lead to qualitatively new performance indicators of the entire production cycle of the fuel and energy complex and the equipment used in this case, operated power systems and units [8].

In the absence of evidence on the extent to which hydrogen is affected by main pipelines and storage facilities created in porous media at UGS, it seems logical to limit the current use of hydrogen and biogas in industrial volumes through the transport system. This should be done considering the risks of exposure, considering the experience of European countries and the United States in the storage and transportation of hydrogen and biogas together with methane, which are already normalized and regulated by national legislation.

5. The concept of territorial hydrogen clusters of the full production cycle

Considering the forecasts of Russia's economic development and the requirements of the international Paris Agreement, it is possible to replace the supply of products from the traditional hydrocarbon energy market with hydrogen and hydrogen-methane mixtures.

According to the researchers, for the issue of production and storage of hydrogen, it is necessary to consider the territorial hydrogen cluster of the full life cycle (production - storage - transportation - use), consisting of a few unconditional components: surplus gas, surplus electricity, storage network in the form of depleted fields or artificially created tanks, transport infrastructure, industrial consumer of hydrogen. Excess volumes of natural gas, as well as the storage of hydrogen and mixtures are expected to be organized through a network of storage facilities in the form of underground gas storage facilities, expansion using depleted hydrocarbon (oil and gas) fields, aquifers and caverns in salt deposits or artificially created storage facilities. It is important to ensure the timely planning and development of above ground and underground storage infrastructures in the form of wells, booster capacities and infrastructure facilities and the creation of regulatory and legal advantages of investments in technologies and infrastructure [9].

The study of the geochemical composition during the storage of hydrogen together with methane and cyclic changes in composition serves as a tool for additional quality control and a way to timely prevent complications and emergencies at facilities. Accordingly, it is proposed to consider the unconditional component territorial hydrogen cluster, including the nodes of hardware analysis of the component composition - hardware and flow chromatographs. Gas metering and quality control devices should be placed at each stage of transportation of hydrogen with methane and pure gas fluids (methane from the main pipeline). Thus, the composition of the gas is controlled, and possible negative changes are prevented. Thus, the composition of the mixtures is controlled, and possible negative changes and consequences are prevented throughout the cluster being created. The proposed hardware control scheme is given on Figure 2.
On the diagram, the blue color indicates the gas coming from the transport system (methane), light green shows the gas flows of hydrogen produced to storage facilities and production, dark blue shows the possibility of supplying a methane-hydrogen mixture to the production. According to the proposals, it is also possible to organize the supply of hydrogen through a special hydrogen pipeline, which reduces production costs and risks.

Control of the component composition is provided from a single Analytical Center using streaming chromatography, high-speed data transmission channels and artificial intelligence technologies. The availability of operational flow control of the composition allows you to improve the quality of storage and transportation, ensure the safety of the technological process and reduce the cost of laboratory analysis.

Figure 2. Scheme of hardware control of the component composition of mixtures

Considering the rapid development of exports and the domestic market of methane-hydrogen mixtures, it is planned to create national and international territorial hydrogen clusters of a full production cycle.

The novelty of the proposed concept lies in the improvement of technologies for automated control of the component composition of stored and transported gas. The availability of operational control of the component composition of the gas will ensure monitoring of resources, identify deviations in the real control mode and improve the quality of products, ensure the safety of the technological process by obtaining critical data in advance and reduce operating costs.
The presented concept creates an additional opportunity to switch to digitalization of control systems and operation of objects of the entire industrial cluster, providing the possibility of streaming control of all major processes in real time, while control issues can be made intelligent using machine learning technologies and artificial intelligence based on the created high-speed communication channels (the use of space groupings and sensor networks) and a geographically distributed computer system to create a system for supporting neural solutions and predicting the operating modes of the entire cluster for the use of industrial hydrogen.

The possibilities of integration of various management systems allow us to build effective management of business processes based on actual data and descriptions of risk models of technologies and processes, minimize risks and errors in making management decisions to control the quality of storage and transportation of hydrogen methane mixtures.

6. Conclusion
To consider the risks, technological and environmental threats to the use of the existing storage network and transit volumes, additional studies of the behavior of hydrogen are required.

However, in the absence of factual data on the degree of impact of hydrogen-methane mixtures on oil and gas pipelines and even more so on underground storage facilities, it seems logical to limit the use of hydrogen and biogas in industrial volumes through the transport system until the consequences are clarified and operating rules are developed. In this perspective, it is necessary to conduct scientific research on the underground storage of non-hydrocarbon gases and their mixtures in aquifers and depleted deposits using promising means of controlling and monitoring the ongoing processes of the industrial hydrogen cluster.

To reduce the negative consequences for infrastructure facilities, it is necessary to ensure continuous hardware monitoring in the form of control of the component composition of gas mixtures at each technological cycle of the industrial cluster, which will ensure the timely detection of emerging complications and negative processes in the form of the likelihood of leaks of hydrogen and its mixtures, timely detection, or prevention of corrosion effects.

The results of the studies require specific processing, considering the formation of national and industry standards and recommendations to guarantee safe, economical and cyclical operation without causing significant damage to the system in the long term of use.

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