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The Influence of Carbon Sequestration in Rocks on the Change in Filtration and Mechanical Characteristics of the Reservoir during Additional Oil Reserve Recovery

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Влияние секвестрации углерода в горных породах на изменение фильтрационных и механических характеристик пласта при доизвлечении запасов нефти

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CCUS (Carbon Capture, Utilization and Storage) is becoming a key technology for achieving a significant reduction in global carbon emissions over the next century, which is why the issues of carbon sequestration in natural porous media have recently received increasing attention in the scientific community. Foreign scientists have obtained some laboratory developments, and carbon sequestration projects have already been implemented in a number of countries. For Russia, carbon sequestration in porous geological media is promising due to the significant potential of underground CO_2 storage tanks, the possibility of using CO_2 to enhance oil recovery, as well as the developed infrastructure of oil and gas fields. The Volga-Ural oil and gas province may become one of the promising regions for the creation of a CCUS cluster due to a combination of such factors on the territory as a significant number of CO_2-emitting enterprises and a huge number of oil and gas traps potentially suitable for the use of enhanced oil recovery methods and / or CO_2 disposal. The article discusses the principles of carbon sequestration in reservoir rocks, the main mechanisms of capture that operate when CO_2 enters a geological repository; it is shown that research in the field of underground CO_2 storage is aimed at reducing the uncertainty in the efficiency of CO_2 storage in rocks, however, the effect of CO_2 on natural porous media is currently poorly understood. Laboratory studies are required, followed by the development of mathematical models of the rocks interaction with various carbon gases types to develop recommendations for optimal modes of carbon injection into the reservoir for the purpose of additional oil recovery in the short term and carbon absorption by the rock and its storage in the long term.

Ключевые слова:
секвестрация углерода, CCUS, декарбонизация, углекислый газ, диоксид углерода, утилизация CO_2, хранение CO_2, подземное газохранилище, увеличение нефтеотдачи, закачка углекислого газа для повышения нефтеотдачи.

Технология CCUS (Carbon Capture, Utilization and Storage – улавливание, использование и хранение углерода) становится ключевой технологией для достижения значительного сокращения глобальных выбросов углерода в течение следующего столетия, в связи с чем вопросам секвестрации углерода в естественных пористых средах в последнее время в научном сообществе уделяется все больше внимание. Зарубежными учеными получены некоторые лабораторные наработки, а в ряде стран уже реализуются проекты секвестрации углерода. Для России секвестрация углерода в пористых геологических средах перспективна ввиду значительного потенциала подземных ёмкостей для захоронения CO_2, возможности использовать CO_2 для повышения нефтеотдачи, а также развитой инфраструктуры нефтегазовых месторождений. Волго-Уральская нефтегазоносная провинция может стать одним из перспективных регионов для создания CCUS-кластера ввиду сочетания на территории таких факторов, как значительное количество предприятий-эмитентов CO_2 и огромное количество ловушек нефти и газа, потенциально пригодных для применения методов увеличения нефтеотдачи и/или захоронения CO_2. В статье рассмотрены принципы секвестрации углерода в породах-коллекторах, основные механизмы улавливания, действующие при попадании CO_2 в геологическое хранилище; показано, что исследования в области подземного хранения CO_2 направлены на снижение неопределенности в эффективности хранения CO_2 в горных породах, однако влияние CO_2 на естественные пористые среды на текущий момент является малоизученным. Требуется проведение лабораторных исследований, последующая разработка математических моделей взаимодействия горных пород с различными типами углеродных газов для разработки рекомендаций по оптимальным режимам закачки углерода в пласт с целью доизвлечения нефти в краткосрочной перспективе и абсорбирования горной породой углерода и его хранения в долгосрочной перспективе.

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Introduction

The problems of carbon sequestration in natural porous media have recently received increasing attention in the scientific community [1, 2]. Foreign scientists have obtained some laboratory practices, and in a number of countries (Norway, USA, Netherlands and Australia) carbon sequestration projects are already being implemented [3–5]. Russia has not had such experience yet, but during the plenary session of the Russian Energy Week on 13.10.2021 the President of the Russian Federation set the goal of achieving carbon neutrality of the economy by 2060. One of the priority and most logical directions for the development of carbon sequestration and achievement of the set goal in Russia is additional extraction of hydrocarbons from the fields which are at the late stage of development. The majority of hydrocarbon fields in Perm Krai is at the final stage of development and can potentially be the targets for carbon sequestration and additional oil production. However, the effect of carbon on natural porous media (rocks) is poorly studied and requires both laboratory tests and the subsequent development of mathematical models of the effect of carbon on the filtration and mechanical characteristics of reservoir in the long term [6, 7]. The predicted result of carbon sequestration in rocks requires justification of the modes of gas injection into reservoirs and long-term storage modes under which the absorption of gases by the rock occurres [8, 9].

The aim of this article was to review the principles of carbon sequestration in reservoir rocks both for the purposes of enhanced oil recovery in the short term and for long-term storage, as well as to analyse the current state of studies of this problem in Russia and abroad.

Analysis of the Principles of Carbon Sequestration in Reservoir Rocks

Carbon sequestration refers to the capture and storage of carbon dioxide (CO_2) to prevent its release into the atmosphere. This process involves the long-term storage of carbon in carbon sinks such as plants, soil, geological formations and the ocean.

For Russia, carbon sequestration in porous geological media is promising due to the significant potential of underground CO_2 storage capacity, the possibility of using CO_2 for enhanced oil recovery, and the developed infrastructure of oil and gas fields [10, 11].

In [12] the basic requirements for the geological object for carbon sequestration are formulated:

– consists of reservoir rocks capable of receiving the injected fluid and providing the necessary injectivity in the stipulated volumes;

– contributes to the preservation of acid gases at the injection site or neutralisation of of the injected fluid aggressive components.

The geological repository should ensure tightness, absence of migration to groundwater and the earth surface and the ability of rocks and fluids of the storage facility to interact with aggressive gas components without formation of potential greenhouse gas leakage channels [13].

Four main mechanisms of CO_2 capture in a geological site have been described in the literature. These are structural trapping, hydrodynamic capture, dissolution of CO_2 in reservoir water and mineral capture [12].

The first type, structural trapping, is caused by the presence of a structural or stratigraphic trap. The CO_2 pumped into the trap is physically unable to migrate outside the trap owing to the existence of an impermeable barrier. This trapping mechanism begins to operate as soon as the gas enters the reservoir.

The second type is hydrodynamic capture which is realised by injecting CO_2 into a deep aquifer filled with saline formation water. Carbon dioxide, having a lower density than formation fluid, will move up the formation to the fluid support and along it, pushing away formation water. As it moves, it will be locked in small structural traps presenting in the aquifer as well as capillary binding to the reservoir water, thus preventing further migration. For the amount of CO_2 injected into such a deep open hydrogeological trap it could be taken more than a million years to travel upwards through highly permeable channels, fractures or faults to reach the surface and enter the atmosphere. Therefore, this storage mechanism is called a hydrodynamic trap [14].

The third type is dissolution of CO_2 in formation water, as a result of which aggressive properties of fluid are neutralised and practically safe storage of CO_2 is provided [12].

The fourth type – mineral capture, is caused by interaction of CO_2 with host rocks and fluids and formation of solid sediments or aqueous solutions. As a result, CO_2 is completely transformed and ceases to exist in its original composition [12].

According to the model of the correlation of active capture mechanisms from time by S. Benson et al. [15], when CO2 enters a geological repository, its retention is first of all promoted by structural trapping, the share of which in the total process is about 80 %. The processes of hydrodynamic trapping and dissolution take longer time, but their importance in the storage mechanism increases rather quickly. Already in 10 years the share of hydrodynamic capture and dissolution in the process of CO_2 storage can reach 50 %. Since sedimentary basins are leaky on a geological, but not necessarily human time scale, the influence of dissolution and mineral trapping mechanisms increases over such a long period (centuries to millennia), allowing CO_2 to be stored in the geological environment for a long period of time [14].

It should be noted that the version of the graph by S. Benson et al. [15] is idealised and illustrates physical mechanisms well, but it should be understood that in real conditions the curves will behave quantitatively and sometimes qualitatively, differently for the reason that reservoir conditions are different in each specific case [16].

According to various studies estimating the amount of CO_2 that can be stored in sedimentary basins, it has been found that brine-filled reservoirs have the largest CO_2 storage capacity, followed by oil and gas reservoirs, and then undeveloped coal seams [17].

The capacity of oil and gas confined traps is small compared to deep aquifers, which are unconfined and eventually bring their water to the surface on a geological time scale. However, the fact that these closed "hydrostratigraphic" traps can reliably hold fluids over geological time and have zones of depletion-reduced pressure which can be filled with CO_2 makes them prime targets attractive for geological storage [17].

The advantages of depleted oil and gas reservoirs also include the fact that their properties such as porosity, permeability, pressure, temperature and total storage capacity are known, and much of the equipment installed on the surface or underground can be reused for storage CO_2.

CO_2 can exist in four phase states – gaseous, liquid, solid and supercritical. In the gaseous state, CO_2 dissolves well in water, partially interacting in it to form carbonic acid. At sharp cooling due to expansion CO_2 is able to pass at once to the solid state, bypassing the liquid phase. Liquid carbon dioxide is not formed in atmospheric conditions and exists only at pressure above 5.1 atm and temperature –56.6...31.1 °C. At temperatures higher than 31.1 °C and pressures higher than 72.9 atm, CO_2 takes the form of supercritical fluid and shows the properties of both liquid (density) and gas (viscosity).

Thus, at sequestration in reservoirs with the depth of occurrence more than 1000 m CO_2 will be in a supercritical state, and in depleted reservoirs of hydrocarbon deposits it can be in a gaseous state due to reduced reservoir pressure [18].

Numerical modelling of storage performance for the purposes of CO_2 sequestration in depleted gas reservoirs is performed in the works [18–20].

According to the results of calculations on storage capacity estimation performed in Eclipse300 simulator it is noted that not all available pore space can be covered by injected CO_2: the actual capacity is influenced by permeability, injection rates and location, number of injection wells [19]. In addition, the storage capacity depends proportionally on the amount of residual gas in the reservoir, and it is reservoirs with low residual fluid content which are the best choice for storage purposes [20].

In cases where the conditions of the geological site are favourable for the formation of CO_2 hydrates, the storage capacity can increase up to 5.8 times (in contrast to disposal in the fully gas phase) due to the transformation of injected CO_2 into gas hydrate, according to modelling data [21]. The modelling was performed in the CMG STARS simulator.

The kinetics of CO_2-hydrate formation leading to CO_2 capture in solid form is fast enough to allow long-term CO_2 storage and CO_2 leakage is completely prevented [21].

In [18] the possibility of carbon sequestration in the North-Stavropol UGS was assessed. The depth of occurrence of the productive horizon (from 650–750 m) and the current thermobaric conditions (reservoir pressure – 3 MPa, and reservoir temperature – 60 °C) are known. It was obtained that during injection CO_2 will not go to supercritical state and will be in gaseous state. Numerical modelling was performed in the TOUGH2 software package. The amount of CO_2 dissolved in the residual and contour waters of the underground gas storage was also calculated in the software package.

It is noted that when CO_2 is used as a gas enhancement agent in depleted gas reservoirs, the quality of the produced gas is significantly reduced as a result of mixing with CO_2. The success of this practice depends on the injection strategy, reservoir characteristics and operating parameters [22]. It is shown in [23] that CO_2 injection in depleted reservoirs is more effective than in the early stages of site development. According to modelling by S. Khan et al. [24], it is found that the higher the CO_2 injection rate, the higher the natural gas recovery will be. In [18], when assessing the feasibility of CO_2 injection for enhanced gas recovery, the modelling results showed rapid CO_2 breakthroughs and concluded that this method should be abandoned, but the reasons for these breakthroughs remain unclear.

Injection into depleted fields has a number of risks in terms of CO_2 leakage upstream through emergency wells and due to corrosive effects of CO_2 on the structures of the existing stock. From the point of view of safety of CO_2 storage, aquifers have an advantage. In Russia, aquifers are widely used as injection facilities, including as underground gas storage facilities. CO_2 storage in aquifers is not currently carried out in Russia, but it has been carried out on an industrial scale in the world since 1970 and is currently recognised as an effective, reliable and safe method of decarbonisation [12].

During consideration of deep saline aquifers it can be noted that there is a practice of CO_2 – water –rock interaction in the process of CO_2 injection [25–28]. This can be explained by the fact that all CO_2 capture mechanisms which can work simultaneously are involved here. The influence of dissolution and mineral capture mechanisms increases: as a result of CO_2 dissolution in the brine carbon dioxide is formed and then chemical reaction of carbon dioxide with the host rocks leads to the formation of new stable carbonate minerals [29].

Dissolution of CO_2 in water changes its chemical composition and physical characteristics. As the concentration of CO_2 in waster rises the viscosity of water increases which reduces its mobility. Formation of new carbon minerals, their dissolution and precipitation can both increase and decrease the size of pores and cracks. When some minerals are dissolved, as a rule, there is a subsequent precipitation of others, and this leads to a repeated change in filtration and capacitive parameters of the reservoir rock [30–32].

As a result of the experiments [25–28] it has been determined that geochemical reactions depend on lithology of the host rocks; most experiments show that changes in mineralogy lead to the increased porosity near the well [25, 28] and its reduction at a distance [28]; the importance of determining the cation release rate is emphasised [26]. Mineral dissolution is confirmed by analysing microcomputed tomography images [25]. Laboratory experiments in the CO_2-water-rock system aimed at determining changes in the mineralogy and porosity of selected reservoir rocks during simulated CO_2 injection should be a mandatory step in selecting CO_2 sequestration site.

For the movement and capture of CO_2 in the subsurface during carbon geosequestration, especially with respect to pore-scale capillary CO_2 capture and structural trapping in low permeability formations, the problem of wettability of different minerals and subsurface rocks with respect to CO_2 is important [33]. Research results show that hydrophilic rocks are the preferred formations for CO_2 storage because they increase storage capacity and localisation reliability [34, 35].

It was shown in [34] that some hydrophobic surfaces, such as oil-wettable carbonates or coal, are intermediate-wettable or CO_2 wettable. Based on the results of the review carried out in [27], it is suggested that silty-clayey rocks can accept any classification of wettability depending on the exact composition of the rock: water wettability, intermediate wettability or CO2 wettability. It is noted that important minerals and rock types such as dolomite, anhydrite, halite, mudstones, and clays have not yet been investigated in terms of CO_2 wettability. It has been emphasized the importance of core collection, processing and preservation procedures, and sample preparation in the laboratory to maintain the original surface wettability.

In addition to rock properties and CO_2 injection scenarios as factors affecting carbon sequestration, in [28] injection well configurations are also considered: from a technical point of view, horizontal injection wells are preferred because they increase storage capacity and reliability of localisation CO_2.

Use of CO_2 for Enhanced oil Recovery

The use of CO_2 for enhanced oil recovery is effective owing to its good dissolving ability. The direction of CO_2 application is injection into the productive formation in order to increase production of high-viscosity oils, condensates, as well as use in depleted fields with a high degree of water cut.

As CO_2 moves through the reservoir, it increasingly dissolves light hydrocarbons and at the same time dissolving in e oil. Dissolution of CO_2 in oil causes it to swell, reduce its viscosity and increase its mobility. Thus, as a result of changes in oil and water properties, relative equalisation of oil and water mobility is achieved, surface tension at the oil-water interface falls down and water wettability of the rock increases. Dissolution of some minerals caused by chemical reactions leads to rock permeability increase. In combination all these facts contribute to more efficient washing off of the oil film. The efficiency of oil displacement may be reduced due to the process of 'finger formation', when CO_2 moves faster in some directions, reaching the field well prematurely [36].

In the case of using CO_2 foam for enhanced oil recovery efficiency growth of oil displacement is achieved by reducing the mobility of CO2 [37, 38]. CO_2 foam can increase oil recovery by up to 200 % compared to foam free CO_2 injection [34].

ORF incremental growth relative to water flooding can be up to 30 % in the case of continuous CO_2 injection into the target reservoir layer (according to hydrodynamic model calculations for the Volga-Ural oil and gas province) [39]. By the end of development about 60% of all injected CO_2 is naturally buried in the reservoir. Part of the carbon dioxide breaks through along with the produced oil, so its re-injection into the reservoir should be provided. In this case 100% burial of all used CO2 will be ensured [34].

The economic feasibility of this method in particular and carbon sequestration in general is associated with the necessity of the selected geological object proximity to the emitters of CO_2 blowout. Thus, about half of all realized projects of oil recovery enhancement by the use of carbon dioxide have been implemented in the world in the fields located near its largest natural sources, namely in the states of Texas and New Mexico (USA) [30].

In the paper [40] it has been carried out the analysis of the efficiency of carbon diozide separation from the produced gas at the fields of LUKOIL-Primoryeneftegas Ltd with its subsequent injection into the reservoirs of depleted fields to increase the production of hydrocarbons as well as to extract high-viscosity oil. It has been made the conclusion about the possibility of developing this direction.

It is known that significant amounts of CO_2, as well as sulfur, nitrogen oxide and sometimes even mercury and other components enter the atmosphere as a part of the products of associated gas combustion. These substances adversely affect the environment. One of the main problems of associated petroleum gas utilization and processing in the regions of Russia is the lack of technological and transport infrastructure. The unprofitability of APG injection into the reservoir for enhanced oil recovery is shown by the example of the oil field of the Udmurt Republic [41], where realization of such variant of APG use requires the construction of a gas pipeline, a hydrogen sulfide purification unit and a booster unit.

In Verkhnechonskneftegaz JSC [42] there were considered two methods of carbon sequestration: injection of APG into a temporary underground gas storage facility for storage and possible subsequent use (this method is already in use) and monetisation of gas into the main gas pipeline "Power of Siberia". According to the results of calculations it was obtained that the implementation of the project on gas monetisation into the Power of Siberia main pipeline is the most expedient and economically beneficial. However, the option with gas injection into the reservoir also makes it possible to meet the requirement for achievement of the useful gas utilization level of 95 %. The choice of the option for each Rosneft subsidiary depends on the volume of gas produced.

According to [39], the scaling of CCUS technologies abroad already leads to a reduction in the capital cost of carbon dioxide capture, which is about 70 % of the total project costs. Further reduction of capture costs will make CCUS projects commercially more attractive.

The Urals-Volga region may become one of the most promising regions for the creation of a CCUS cluster due to the presence of a significant number of CO_2-emitting enterprises and a huge number of oil and gas traps in the Volga-Ural oil and gas province, potentially suitable for enhanced oil recovery and/or CO_2 burial methods [39].

Analysis of Rock Response (Deformation) to Carbon Injection

One of the problems associated with CO_2 injection into geological formations is pressure increase. An increase in reservoir pressure can cause noticeable changes in rock properties in the vicinity of the injection zone, namely mechanical deformations: formation of new fractures or reactivation of existing faults [43, 44].

For example, the In Salah project in Algeria [45] was suspended due to unexpected geomechanical deformations resulting from excessive pressure build-up and triggering a CO_2 breakthrough into an old well. Pressure build-up in the reservoir occurs due to a combination of viscous forces and multiphase flow phenomena associated with the interaction between the injected CO_2 and the fluids. The amount of the pressure increase depends primarily on the injection rate and the permeability and thickness of the formation.

Injection of CO_2 at high rates can lead to pressure increases above the fracture pressure of the reservoir and fluid support. It is noted the effect of residual gas on the rate of pressure rise as well as the stability of injection rates at high injection rates. It is recommended that low injection rates be selected to ensure favourable injectivity when residual gas levels in the reservoir are significant [20].

The geological conditions and characteristics of the host CO_2 reservoirs must be subject to special requirements to ensure long-term safe storage. The physical and chemical properties of CO_2 can adversely affect the shielding properties of the fluid reservoir and the thinner interlayers that separate the reservoir layers. Therefore, it is important to study the mineral composition, permeability, stress state, and fractures of the fluid bearing and reservoir that will host CO_2 when selecting a depleted oil and gas field as CO_2 natural storage facility.

Conclusion

A promising area of carbon sequestration in Russia is the injection of carbon dioxide into depleted oil and gas traps. However, the interaction of rocks with CO_2 is currently poorly studied. Mechanisms of both short-term and long-term CO_2 storage in oil reservoirs are accompanied by complex evolution of porosity and permeability properties. Dissolution of CO_2 in water changes its chemical composition and physical properties. The mechanism of mineral trapping is accompanied by dissolution of some minerals and precipitation of others. It is required to carry out laboratory studies, subsequent development of mathematical models of interaction of rocks with different types of carbon gases to develop recommendations on optimal modes of CO_2 injection into the reservoir in order to recover oil in the short term and absorption of carbon by rocks and its storage in the long term.

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