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Analysis of International Experience of Carbon Dioxide Injection in Various Geological and Technological Conditions of Oil Field Development

Konstantin A. Zayakin, Aleksandr I. Menshikov , Sergey G. Ashikhmin, Aleksandr A. Melekhin, Sergei V. Galkin

Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

Анализ международного опыта закачки углекислого газа в различных геолого-технологических условиях разработки нефтяных месторождений

К.А. Заякин, А.И. Меньшиков, С.Г. Ашихмин, А.А. Мелехин, С.В. Галкин

Пермский национальный исследовательский политехнический университет (Россия, 614990, Пермь, Комсомольский пр., 29)

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Due to the growth of carbon dioxide in the atmosphere, reducing its emissions undoubtedly belongs to one of the most priority environmental tasks. At the same time, its injection into the reservoir in order to increase oil recovery can be considered as a promising method of CO_2 utilization. The article considers the domestic and foreign experience of using this technology. The following methods used to supply CO_2 to the reservoir were analyzed: injection of carbonized water, continuous injection of CO_2, displacement of oil by cyclic injection of CO_2 and water, as well as a number of alternative technologies. The processes of mixing, limited-mixing and immiscible displacement were described when using gas methods to increase oil recovery, thermobaric conditions of these processes were determined. The influence of the minimum mixing pressure on the efficiency of carbon dioxide injection was analyzed, the analysis of theoretical and experimental methods for studying these processes was carried out. The impact of carbon dioxide on the corrosion of field equipment was assessed. Conclusions about the necessity of using pipes made of high-alloy steel with a high chromium content with the additional use of protective nonionic surfactants when injecting carbon dioxide were drawn.

Ключевые слова:
повышение нефтеотдачи, закачка углекислого газа, минимальное давление смесимости, коррозия промыслового оборудования, поверхностно-активные вещества.

В связи с ростом углекислого газа в атмосфере снижение его выбросов, несомненно, относится к одной из наиболее приоритетных экологических задач. При этом в качестве перспективного способа утилизации CO_2 может рассматриваться его закачка в пласт с целью повышения нефтеотдачи. Анализируется отечественный и зарубежный опыт применения данной технологии. Проведен обзор и анализ методов, используемых для подачи CO_2 в пласт, среди которых к наиболее часто применяемым на практике относятся: закачка карбонизированной воды, непрерывное нагнетание CO_2, вытеснение нефти циклической закачкой CO_2 и воды, а также ряд альтернативных технологий. Описаны процессы смешивающегося, ограниченно-смешивающегося и несмешивающегося вытеснений при применении газовых методов увеличения нефтеотдачи, определены термобарические условия данных процессов. Произведен анализ влияния минимального давления смесимости на эффективность закачки углекислого газа, проведен анализ теоретических и экспериментальных методов исследования данных процессов. Выполнена оценка влияния углекислого газа на коррозию промыслового оборудования. Сделаны выводы о необходимости при закачке углекислого газа использования труб из высоколегированной стали с высоким содержанием хрома с дополнительным использованием защитных неионогенных поверхностно-активных веществ.

© **Konstantin A. Zayakin** – 1st Category Engineer (tel.: +007 (961) 758 69 54, e-mail: zayakin65@gmail.com).
© **Aleksandr I. Menshikov** – Group Leader (tel.: +007 (342) 239 10 70, e-mail: alexandr.menshikov@girngm.ru).
© **Sergey G. Ashikhmin** (Author ID in Scopus: 6603057955, ORCID: 0000-0001-7850-3415) – Doctor in Engineering, Professor at the Department of Mine Surveying, Geodesy and Geoinformation Systems (tel.: +007 (342) 219 84 22, e-mail: A_s_g_perm@mail.ru).
© **Aleksandr A. Melekhin** (Author ID in Scopus: 55531747500, ORCID: 0000-0002-0737-1360) – PhD in Engineering, Associate Professor at the Department of Oil and Gas Technologies (tel.: +007 (342) 219 82 07, e-mail: melehin.sasha@mail.ru).
© **Sergei V. Galkin** (Author ID in Scopus: 36711675500, ORCID: 0000-0001-7275-5419) – Doctor in Geology and Mineralogy, Professor (tel.: +007 342 219 81 18, e-mail: gnfd@pstu.ru). The contact person for correspondence.

© **Заякин Константин Андреевич** – инженер 1-ой категории (тел.: +007 (961) 758 69 54, e-mail: zayakin65@gmail.com).
© **Меньшиков Александр Игоревич** – руководитель группы (тел.: +007 (342) 239 10 70, e-mail: alexandr.menshikov@girngm.ru).
© **Ашихмин Сергей Геннадьевич** (ORCID: 0000-0001-7850-3415) – доктор технических наук, профессор кафедры «Маркшейдерское дело, геодезия и геоинформационные системы» (тел.: +007 (342) 219 84 22, e-mail: A_s_g_perm@mail.ru).
© **Мелехин Александр Александрович** (ORCID: 0000-0002-0737-1360) – кандидат технических наук, доцент кафедры «Нефтегазовые технологии» (тел.: +007 (342) 219 82 07, e-mail: melehin.sasha@mail.ru).
© **Галкин Сергей Владиславович** (ORCID: 0000-0001-7275-5419) – доктор геолого-минералогических наук, профессор (тел.: +007 342 219 81 18, e-mail: gnfd@pstu.ru). Контактное лицо для переписки.

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Introduction

The overwhelming share of fields in "old" oil and gas producing regions are currently at a late stage of development. Analysis shows that in Perm Krai the average water cut for the majority of large fields exceeds 85 %, which puts their reserves in the category of hard-to-recover reserves. It is possible to increase the efficiency of waterflooding, which has been the main development method for many years, by using gas enhanced oil recovery (GOR) methods [1, 2]. One of the promising methods of increasing the oil recovery factor (ORF) is the injection of carbon dioxide (CO_2) into productive formations.

It should be mentioned that the use of CO_2 as an injection agent, in addition to increasing the oil recovery factor, also solves environmental problems. For example, in 2022 the content of carbon dioxide in the Earth's atmosphere reached another maximum increasing the urgency of controlling the content of greenhouse gases, the basis of which is CO_2. Thus, CO_2 injection into productive formations can be regarded as a complex geological and engineering intervention (GEI) solving technological and environmental problems simultaneously. This study reviews technologies for the beneficial use of CO2 aimed at increasing oil production, and considers the problems of its influence in dynamics on the characteristics of process equipment.

Review and Analysis of the Efficiency of the Applied Methods of Carbon Dioxide Injection into Productive Formations

For the territory of Russia CO_2 injection projects are considered as highly promising, since the situation of existence of anthropogenic sources of CO_2 near depleted fields is generally quite typical [3]. According to the literature review conducted by the authors, the use of CO_2 injection can significantly increase oil production volumes. In [4] it is shown that for the fields of Western Siberia the production volume at CO_2 injection is 60 % higher in comparison with water injection. Also the effective technology of carbon dioxide injection under water-oil contact is considered in this work.

In [5] the authors remark that due to the use of carbon dioxide it was possible to achieve an increase in the oil recovery factor by 18 %.

The obvious problematic aspects of CO_2 injection include increased corrosion of equipment of production and injection wells. It should be noted that at incomplete mixing of CO_2 with oil light fractions are released from it, which leads to reduction of oil mobility [6]. At the same time, a decrease in the medium temperature during CO_2 dissolution increases the probability of formation of asphaltene-resin-paraffin deposits (ARPD) [7]. In addition, gas injection provides for special technological requirements to ensure industrial safety at oil and gas enterprises [8].

It is known the following technologies of CO_2 injection into the reservoir to enhance oil recovery:

1. Injection of carbonized water (i.e. water pre-saturated with carbon dioxide). The implementation of such technology in the oil field is relatively simple. When injecting carbonized water, there is a low CO_2 consumption (water content is 4–5 %). At the same time, enhanced oil recovery is estimated to be 14 % higher compared to the standard waterflooding methods [9].

2. Continuous CO_2 injection. The main advantage of this method is the possibility of achieving a high coefficient of oil displacement, formed due to the formation of an oil front which is promoted by carbon dioxide. The disadvantages of this technology include the possible formation of a highly viscous unstable medium which, in turn, can lead to a breakthrough of carbon dioxide to injection wells.

3. Oil displacement by cyclic injection of CO_2 and water. This method with alternating injection of CO_2 and water is the most economical and can be effective for heterogeneous formations. According to [10], application of this technology allows in some cases to obtain oil recovery factor 12 % higher than at continuous injection of carbon dioxide, and 30 % higher than at water injection.

4. CO_2 injection together with associated petroleum gas (APG). The technology can also be realized with direct supply of APG if its main component is carbon dioxide. In [11] it is shown that at realization of this method oil recovery factor increases by 6 %, and with the use of sequential injection of APG and water the growth can reach 11–14 %.

For various gas injection technologies, modern hydrodynamic modeling packages provide the possibility of numerical calculations of fluid production dynamics by wells [12–14].

In [15] on the basis of a mathematical model the influence of the volume of injected CO_2 on the GTA efficiency was analyzed. When injecting pure CO_2 with increasing injection volumes, a gradual increase in oil production was found, while the growth of injection rate was also noted as a favorable factor for GTA efficiency. Analysis of temperature conditions of productive formations allowed [15] to draw conclusions that there is a decline in oil production in the range up to 50 °C, after that the dynamics changes and its growth begins.

In [16] with the help of laboratory studies it was shown that the optimal pressure during CO_2 injection is the proximity of bottomhole pressures to the oil saturation pressure, and the optimal CO_2 temperature during injection should be close to the reservoir temperature.

One promising way to use carbon dioxide for enhanced oil recovery is to inject it in a supercritical state (SCS), i.e., in a liquid state of carbon dioxide in which it is maintained at or above critical temperatures and pressures.

In this case, the solvent capacity of CO_2, provided that the temperature is constant, increases with an increase in the density of the injected agent [17].

At the realization of the SCS technology an important property of CO_2 is its adsorption capacity which depends on the injection pressure [18]. As a result, at pressures above 25 MPa and a temperature of 90 °C it is observed a miscible displacement regime at which the coefficient of displacement of oil by carbon dioxide was 0.96 [19].

In [20], the problems of the efficiency of CO_2 injection into SCS for enhanced oil recovery of productive formations represented by low-permeability sandstone are comprehensively considered. Particular attention is paid to the effects of asphaltene deposition, which is linked to the effect of CO_2 injection on the permeability, porosity and wettability of the reservoir. According to calculations, during flooding with CO_2 injection in a supercritical state, the oil recovery factor reaches 45 %. It has been established that oil production in the process of CO_2 injection into SCS declines rapidly with an increase in the number of cycles, and the main volume of production (about 80 %) falls on the first two cycles. At the same time, the injection of CO_2 in a supercritical state leads to the deposition of asphaltenes in porous media, which worsens the permeability and porosity of the formation [20].

In [21] it is shown that in comparison with the gaseous state, carbon dioxide in SCS has higher coefficients of diffusion and mass transfer at the interface of phases. The intense diffusion of supercritical CO_2 into light oil leads to faster changes in oil properties, which can be used to optimize enhanced oil recovery technology.

One of the main problems arising during CO_2 injection is its possible breakthrough into injection or production wells. In this regard, there is a need to limit the mobility of the injected agent. One way is to create foamy CO_2, which reduces the rate at which gaseous CO_2 is released, and also reduces the likelihood of a possible breakthrough by the gas cap reduction. In [22], a phenomenological model was developed, on the basis of which the problem of estimating the foam balance in a rock cell was solved. In [23] it has been performed a comparison of CO_2 foam injection technologies and the use of nanoparticles. It is shown that by using this technology it is possible to increase the ORF by 13 %.

In the paper [24], there were carried out the experiments on measuring the minimum miscibility pressure and experiments with the foaming of enriched gas, which showed an increase in the oil recovery factor by 19 %. In general, the problematic point of this technology is the instability of the foam under conditions of high temperature and high salinity. The stability of the foam can be improved by introducing surfactants, including such nanoparticles as SiO_2.

Analysis of the Effect of Minimum Mixing Pressure on the Carbon Dioxide Injection Efficiency

At application of gas EOR it is possible to distinguish processes accompanied by miscible, limited-miscible and non-miscible displacement of oil by gas. For example, in [25] it is shown that the use of carbon dioxide can increase oil production by 21 % and reduce its viscosity by 63 % at miscible displacement. The effect of miscible displacement is 38 and 16 % higher than that of limited-miscible and immiscible displacement, respectively.

The most effective methods are those that provide miscible displacement, when gas is completely dissolved in the formation oil due to a decrease in surface tension at the interface [26]. This type of displacement is achieved at the minimum miscibility pressure (MMP), which is the main criterion affecting the efficiency of CO_2 injection technology. In determining the MMP with laboratory equipment the most common is the slim tube test [27–29]. In [29], the MMP was calculated by the equation of state and the McLavani correlation dependence. With the help of the slim tube experiment it was possible to improve the accuracy of the MMP calculation and to correct the empirical formulas.

One of the promising areas, as shown above, is the possibility of supplying not pure CO_2, but its mixture with APG. The determination of MMP of a mixture of CO2 and APG for the use of cyclic gas injection technology was studied in [30]. It is shown that the MMP of the mixture begins to increase with a mass fraction of APG of more than 20 %. At the same time, depending on the geological and technological conditions of development, the optimal shares of CO_2 and APG in the mixture are 75–95 and 5–25 %, respectively [30].

In [31], the authors consider the application of gas methods of enhanced oil recovery for reservoirs with large depths and low permeability. The assessment of the minimum miscibility pressure using correlation dependencies showed that when APG and CO_2 are injected, oil will be displaced in the miscible mode, and a limited miscibility is established for dry gas. According to numerical experiments, APG injection has a higher oil recovery factor compared to water injection [31].

In general, a review of the world experience in the applicability of CO_2 injection methods (USA, Canada, Turkey, etc.) shows its high prospects in various geological and technological conditions of oil field development [32–34]. The ranges of geological and physical characteristics of production facilities using the technology are as follows: reservoir pressure – 3.1–12.7 MPa; porosity – 11–23 %; permeability – 0.017–400 μm2; the oil density is 953–1044 kg/m^3, the viscosity of oil is 114–936 mPa•s [35, 36]. In general, it can be concluded that the characteristics of the producing reservoirs of Perm Krai correspond to the conditions with the successful realization of CO_2 injection. At the same time, the technology is mainly used in conditions of increasing oil recovery of high-viscosity oils, which must be taken into account in its implementation.

Analysis of the Methods of Reduction of Carbon Dioxide Impact on Field Equipment

The most vulnerable to corrosion during CO_2 injection are the following pieces of equipment: tubing, production strings, and downhole pumping equipment (DPE). Aggressive environment appears when the metal surface interacts with carbonic acid formed in the process of CO_2 dissolution in water, resulting in carbonic acid corrosion. As the concentration of CO_2 becomes higher, the aggressiveness of the produced medium also increases. High concentration of carbon dioxide contributes to the growth of intensity of deposition of carbonate ions Ca, Fe, Na, etc. on the metal surface. One of the fundamental factors influencing the process of carbon dioxide corrosion is temperature [37]. With increasing temperature there is an increase in the rate of chemical reactions, diffusion rate and solubility of corrosion products protecting the surface [38].

In [39] the corrosion cracking patterns of steels, which has the main influence on the possibility of using casing and tubing for production at high concentrations of carbon dioxide, are described. It is shown that corrosion resistance at high concentrations of CO_2 is achieved at using steel of martensitic class. However, carbon (St20 and X65) and low-alloy steels (0,05–0,2 % of chromium) are most often used. The corrosion rate of such steels can reach high values. Tests [39] have shown that they undergo corrosion damage with the formation of deep defects, and the rate of localized corrosion reaches 1 mm/year. It is also worth noting that pitting processes are also found in systems containing O_2 and H_2S [40].

High-alloy steel pipes are widely used in CO_2 injection at oil and gas facilities. In [41], it was studied the corrosion behavior of X65 steel with different chromium content which was exposed to saturated CO_2 at 60 °C and 100 bar at different immersion times. No significant formation of corrosion products was observed in the early stages. The corrosion resistance of the materials increased with increasing Cr content. At the same time, in the experiments with the absence of protective films, with the increase of Cr content the dissolution of metal decreased, which reduced the corrosion rate by 2.5 times.

Another reason for equipment or pipelines corrosion is high salinity of water as well as thermobaric conditions. In this case, to provide protection for the equipment used more corrosion resistant steels are required or alternative means of protection, e.g. corrosion inhibitors or others are required [42].

In general, the results of the analysis of the impact of aggressive environment show a complete absence of corrosion manifestation in using martensitic class steels and corrosion inhibitors.

In [43], a series of laboratory studies of corrosion under the conditions of the supercritical state of CO_2 were carried out. Based on the tests of the corrosivity of produced water with a mineralization of 55 g/l with constant passage of CO_2 through it, it was shown that nitrogen-containing modified nonionic surfactants (NIS) exhibit a protective ability to the metal of the order of 98% at 0.5 m/s flow rate; 49 % – at a flow rate of 2 m/s at an inhibitor dosage of 25 mg/L. An increase in the protective properties of surfactants above 75 % is observed with the addition of a nitrogen-containing cationic surfactant (CS) and a phosphorus-containing anionic surfactant (AS). The results obtained can be used in the selection of inhibitory compositions [44].

In [45] it is noted that at a supercritical state, CO_2 can have solvent properties, so it is necessary to pay attention to the safety of rubber and plastic components that are used in equipment. The effect of CO_2 on three types of rubber materials was studied in [46] by simulating conditions typical for injection wells. According to the analysis, rubber samples exposed to liquid CO_2 showed greater reactivity compared to CO_2 gas. It is mentioned that the corrosion resistance of fluorocarbon rubber and hydrogenated nitrile butadiene rubber is better than that of nitrile butadiene rubber.

In [47] it was determined that the presence of water in the produced fluid is one of the key factors affecting the intensity of corrosion processes. In CO_2 transport and injection systems, accidental ingress of water can cause corrosive damage, requiring water content reduction and rapid control.

Conclusion

Thus, a comprehensive study of the experience of applying enhanced oil recovery technologies by using carbon dioxide as a working agent has been carried out. The main and alternative methods of CO_2 injection into productive formations are considered, the analysis determining the main advantages and problematic points of the technology realization has been carried out.

Methods for determining the minimum mixing pressure are described. The optimal conditions for the applicability of CO_2 injection are indicated, and a conclusion about the prospects for using the technology in the oil fields of Perm Krai has been made. To minimize the impact of carbon dioxide corrosion on field equipment it is recommended to use pipes made of high-alloy steel with a high Cr content, as well as the use of protective non-ionic surfactants.

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