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TECHNICAL AND ECONOMIC ASPECTS OF MONITORING CO_2 DISTRIBUTION IN GEOLOGICAL STRUCTURE USING GRAVIMETRIC METHODS

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ABSTRACT

The article addresses the reduction of carbon dioxide (CO_2) emissions by placing them in geological structures. The technical and economic aspects of monitoring the distribution of carbon dioxide in geological structures, including technical, economic and environmental issues related to long-term storage of CO_2 in geological formations, are studied. The need to ensure the reliability of carbon dioxide disposal and control their condition in the layers of the underground storage is considered. The main aspects of monitoring the distribution of carbon dioxide in the geological structure by gravimetric methods, including by the volume of the structural trap during its disposal, are studied. The article studies the features of the distribution of carbon dioxide in the reservoir with the initial saturation of the reservoir with low-density reservoir fluid and the possibility of activating gas-dynamic risks. The issue of the distribution and rate of distribution of carbon dioxide by the volume of the natural trap is considered. It is substantiated that gravity prospecting monitoring allows tracking the current state of the geological structure into which CO_2 is injected and timely strengthening control over the tightness of old wells during the distribution of carbon dioxide in the area of their location. The possibility of using gravimetric monitoring of the distribution of carbon dioxide in the geological structure is substantiated and the possibility of constructing indicator maps and graphs characterizing the distribution of fluid in the trap is considered.

Keywords: technical and economic aspects; deposit; carbon dioxide (CO_2); gravity exploration; reservoir; structural trap; CO_2 placement; geological structure.

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1. Introduction

Reducing carbon dioxide (CO_2) emissions is an important step in slowing climate change and creating a more sustainable future. Minimizing CO_2 emissions and making positive environmental changes are key goals. For example, the European Union plans to become a carbon-neutral region by 2050, allocating significant resources to innovation and decarbonization. Carbon dioxide reduction policies are aimed at combating climate change and include a variety of measures. Reducing CO_2 emissions is a complex and multifaceted challenge that requires joint efforts by the international community. CO_2 emissions, mainly of anthropogenic origin, contribute to climate change, and their reduction is essential in addressing this phenomenon.

One of the solutions to these problems is carbon capture and storage (CCS) systems, which capture CO_2 generated from fossil fuel combustion at power plants and industrial processes and store it (including in deep geological formations , preventing its release into the atmosphere) [1, 2].

The reduction of carbon dioxide emissions (CO_2 sequestration) by industrial enterprises (including the oil, gas, chemical, and energy industries) is accompanied by economic benefits through the use of tax measures, emissions trading systems, government subsidies, and the introduction of new technologies. These instruments encourage companies to transition to cleaner production methods and help reduce their environmental impact. As is known, CO_2 sequestration represents a set of technologies and methods aimed at capturing, transporting, and securely storing CO_2 released from industrial activities in order to prevent it from entering the atmosphere.

The techno-economic aspects of monitoring carbon dioxide distribution in geological structures include technical, economic, and environmental issues related to the long-term storage of CO_2 in geological formations (table 1).

In the process of geological storage of CO_2, the distribution of carbon dioxide in geological structures is an important

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Table 1

Technical and economic aspects of monitoring the distribution of carbon dioxide in geological structures

Aspects	Result
Technical	Selection of suitable places for CO_2 storage – layers of depleted hydrocarbon deposits and/or mineralized aquifers. The physical properties of the rock and fluids, the possibility of chemical interaction of CO_2 with the host rocks are taken into account
Economic	Costs of CO_2 burial – depend on the characteristics of the geological reservoir. Economic feasibility of CO_2 sequestration projects – it is necessary to determine the conditions under which the projects become profitable. For example, the cheapest option is to bury CO_2 in depleted oil and gas fields on land
Ecological	Risks of leakage – there is a possibility of stored CO_2 leaking back into the atmosphere, which could offset the environmental benefits of sequestration. Uncertainty of geological stability – long-term CO_2 storage requires assurance that the selected formations will be geologically stable over millennia.
The technical and economic features of monitoring the distribution of CO_2 in geological structures are related to the need to ensure safe and long-term storage of CO_2, as well as economic factors and the regulatory framework. These features concern technical aspects, economic issues and the regulatory framework	

issue that requires special study. Since CO_2 is injected into underground rock formations such as depleted hydrocarbon (HC) reservoirs, deep saline aquifers, and unmineable coal seams, the main goal is to capture and store carbon dioxide generated from industrial emissions to reduce the impact of emissions on global climate change. Monitoring the distribution of CO_2 in geological structures is a process aimed at ensuring its safe and long-term storage in underground reservoirs (geological formations). The primary objective is to prevent gas leakage, including into underground drinking water sources, and its escape to the surface.

Monitoring the distribution of CO_2 in geological structures is one of the key aspects of carbon capture, utilization, and storage (CCS) projects, enabling the risk assessment of its leakage from storage. Monitoring helps to identify potential leakage pathways, measure its migration rates, and ensure long-term safe storage of CO_2 in geological formations. It includes assessing geological conditions, modeling the behavior of CO_2 in storage, and controlling the integrity of the storage system.

Various methods are used for monitoring the distribution of CO_2 in geological structures, including:

- Seismic monitoring and imaging — providing 3D illustrations of CO_2 migration pathways;
- Resistivity imaging — indirectly tracking CO_2 migration and distribution through changes in electrical resistivity;
- Isotopic tracing — assessing the origin, migration paths, and transformations at the site of CO_2 deposition;
- Core flow experiments — measuring CO_2 permeability and reactivity in rock samples.

When evaluating geological structures for CO_2 storage, it is necessary to consider:

- Reservoir suitability for long-term retention — for example, the presence of a caprock that prevents CO_2 dissipation;
- Sufficient burial depth — at such depths, CO_2 exists in a liquid or supercritical state with relatively high density;
- Absence of conductive faults — as the sealing integrity of caprock depends on fault tectonics.

Several CO_2 storage projects with monitoring systems have been implemented worldwide. For example, the Norwegian Sleipner Project stores CO_2 in a saline aquifer without leakage, thanks to geological studies confirming the seal integrity of the zone. This project was the first commercial CO_2 storage project, characterized by high CO_2 content (up to 9%), implemented by the operator Statoil (Equinor). After Norway introduced a greenhouse gas emissions tax, the project provided for CO_2 injection into the Utsira sandstone formation at a depth of 800–1000 m below the North Sea floor. Since 1996, up to 1 million tons of CO_2 have been injected annually into the reservoir, with a storage area of about 26000 km² and an estimated capacity of more than 42 million tons of CO_2. The project became a reference case in developing the EU directive on geological CO_2 storage.

The Weyburn Project in southeastern Saskatchewan, western Canada, enables CO_2 injection into dolomitic and limestone oil reservoirs, with groundwater chemistry monitoring conducted prior to CO_2 injection and at 11 intervals over a four-year period following injection.

Analysis of implemented CO_2 storage projects (carbon sequestration technologies, CCS) shows that they involve certain economic aspects, including cost, revenue, incentives, and risk analysis. These aspects are important for justifying the economic feasibility of projects and defining the conditions under which they become cost-effective. There is no single definitive assessment of CCS cost parameters, as most projects are demonstration-scale. Additional revenue from CO_2 utilization, which is considered a reduction in greenhouse gas emissions, may be obtained within the framework of international conventions and post-Kyoto mechanisms.

Gas migration from underground storage can be caused by geological changes (rock movements), excessive injection pressure, reactions between CO_2 and host rocks, and other factors [1-3]. Risks include destruction of host rocks under CO_2 influence (swelling, fracturing, low-temperature effects); damage to well casings and cement seals, which may lead to gas leakage. Leakage risks cannot be quantitatively assessed, but most experts note that even a 1% CO_2 leakage could lead to irreversible consequences. Therefore, monitoring the distribution of CO_2 in geological structures is aimed at minimizing potential risks and improving project efficiency, with gravimetry being one of the effective approaches [4-11].

The development of the gas-chemical industry is accompanied by increasing greenhouse gas emissions requiring their utilization. According to modern requirements, industrial enterprises must limit CO_2 emissions within the framework of carbon regulation legislation. The goal of this policy is to create conditions for sustainable and balanced economic development while reducing CO_2 emissions. Accordingly, the provisions of legislative acts include:

- State accounting of emissions — maintaining a CO_2 emissions registry, which serves as a state information system;
- Setting emission reduction targets — established taking into account the characteristics of applied technologies, investment volumes, and other factors.

Government measures to incentivize companies to reduce greenhouse gas emissions are the most important factor in this policy (table 2).

Enterprises have the right to develop climate projects to reduce CO_2 emissions, which involve calculating the allowable volume of emissions and analyzing ways to decrease them — for example, technical re-equipment of facilities, installation of treatment systems, and filters. The economic aspects of industrial enterprises related to CO_2 emission reduction include legislative measures, tax mechanisms, emissions trading systems, and technological solutions. These aspects are aimed at encouraging companies to reduce CO_2 emissions in order to limit the negative impact of their activities on the climate.

The techno-economic efficiency of monitoring CO_2 distribution in geological structures using the gravimetry method (gravity survey) is determined by the possibility of studying the Earth's gravitational field, which reflects the density distribution of the rocks forming the structures. This method makes it possible to: identify structures hidden by sedimentary rocks and inaccessible to conventional geological methods; determine the conditions and parameters of occurrence of anomaly-forming objects (depth, shape, and size) based on local gravity anomalies; and account for the effect of masses located above the observation point in borehole gravity surveys [2].

The techno-economic characteristics of monitoring include the features of methodology, equipment, data processing, and interpretation of results. A comparison of geological and gravimetric data shows that there may be either a direct correlation between gravity anomalies and known geological objects, indicating the identity of geological structures and gravity field sources, or an indirect, mediated relationship of field features with geological elements. The reliability of interpretation depends on the completeness and accuracy of prior information: geological and petrophysical data, drilling results, and other geophysical methods [4-11].

One of the methods of reducing CO_2 emissions is the development of carbon capture and storage (CCS) technologies. These technologies allow capturing carbon dioxide from industrial emissions and storing it in underground reservoirs. One of the by-products of gas-chemical production is CO_2. The issue of carbon dioxide emissions into the atmosphere, as well as the greenhouse effect in general, is relevant worldwide, and solutions are being developed through numerous studies [12-14]. A number of researchers point to the possibility of using CO_2 for enhanced oil and gas recovery, which confirms the feasibility of utilizing underground geological structures for carbon dioxide storage [15–17].

Natural structural traps with certain thermobaric conditions ensure the retention of injected CO_2 at reservoir pressure, which is restored by the end of injection to the initial formation pressure. However, the experience of using natural gas in underground storage and injecting associated petroleum gas into temporary underground storage has shown that the technological regime during injection may be accompanied by gas-dynamic risks in the reservoir system [18-20]. This is related to the growth of the pressure funnel, uncontrolled distribution of gas within the pore volume, and a reduction in the operational life of the storage. Regulation of the operation of the storage site (injection pressure, bottomhole pressure, distribution of reservoir pressure within the working pore volume) is relatively simple with a dense network of production-injection and monitoring wells, as well as during cyclic changes in the technological regime in summer and autumn-winter periods [2].

Placing CO_2 into a reservoir initially saturated with a lower-density formation fluid may activate gas-dynamic risks. Therefore, one of the issues in this process is the distribution and rate of CO_2 spread within the volume of the natural trap.

This paper outlines approaches for developing and implementing methods to control the spread of CO_2 within the pore volume of a structural trap under varying fluid saturation conditions.

The placement of CO_2 in depleted reservoirs must be carried out not only while maintaining trap integrity but also ensuring the absence of lateral CO_2 flow along the trap caprock [21, 22]. Therefore, when injecting CO_2 into a reservoir, monitoring its distribution throughout the formation becomes a critical issue.

Monitoring methodologies must, above all, meet the requirements for accuracy and reliability in determin-

Table 2

Government measures to stimulate companies to reduce carbon dioxide emissions

Legislative measures	Taxes	Emission trading
– emission regulation (the state sets regulatory limits for each type of gaseous substances, for exceeding which a fine is imposed); – creation of an emissions register (this regulates the need to register enterprises that emit greenhouse gases in the register); – setting emission reduction targets for economic sectors (target indicators are set taking into account the specifics of the technologies used, the volume of investment and other factors).	– carbon tax (the company pays the state a fee for its emissions. Some emissions may be free for the company, however, after a certain threshold, a fee is charged). – environmental («green») taxes (the tax is included in the price of the product, the production of which incurs environmental costs. In this case, the company is forced to independently seek ways to reduce emissions and reduce the tax burden).	– carbon quotas - a limit on greenhouse gas emissions. Enterprises that do not meet the quotas can buy the missing carbon units from other companies that have successfully mastered eco-technologies. – the «cap and trade» principle: the regulatory body determines the overall emission limit for the industry, then it is divided into quotas, which are distributed among those responsible. If enterprises have excess emissions, they can «sell» them, and if there is not enough, they can «buy» more.

ing the «gas-water» contact. Nevertheless, simplicity and cost-effectiveness of the method are also important factors. Accordingly, the choice of a suitable monitoring methodology can be built on selecting the simplest and most economical option, followed by assessing its reliability and drawing conclusions about the validity of its application [21].

2. Materials and methods

The research methods are based on the analysis and synthesis of field data related to the studied problems, as well as on the results of the author's own analytical and theoretical research using field and laboratory data. The author's analytical studies were carried out on the basis of theoretical relationships with the application of modern methods. Fundamental concepts of gravitational forces and the definitions of hydrocarbon reservoir regimes were also applied.

3. Results

To address the issue of reducing CO_2 emissions:

- the feasibility of applying gravimetric monitoring for tracking the distribution of carbon dioxide in a geological structure has been substantiated;
- the possibility of constructing indicator maps and graphs to characterize the fluid distribution within the trap has been considered.

4. Discussion

One of the simplest and most cost-effective methods is gravimetric monitoring, which is based on recording changes in the Earth's gravitational field. Gravimetry is successfully applied not only in the oil and gas industry but also in other sectors. In addition, the potential of gravimetry is considered in the study of various components of the Earth system, including the hydrosphere, lithosphere, and the climatic characteristics of the Earth's surface [4-11].

During gravity surveys, measurements are obtained that describe the gravitational field generated by the underlying rock strata. When an anomalous change in mass occurs within the investigated cross-section at a given point, the research object becomes the change in gravitational acceleration at that point, expressed as $\Delta g = g_0 - g_1$, where indices 0 and 1 denote the initial and repeated observation cycles, respectively. Importantly, when calculating the change in gravitational acceleration at a specific point, the components of gravitational forces explained by the unchanging part of the section cancel each other out.

Since the mass of a body equals the product of its volume and density, it is reasonable to assume that gravitational acceleration will depend on the volume in which an anomalous change in mass occurs and on the density of the substance within that volume. It is evident that in hydrocarbon reservoirs with a gas regime, the reservoir volume is by definition constant, and in this case, the change in gravitational acceleration will depend entirely on the change in the density of the fluid filling the pore volume of the reservoir. Let us now consider gravitational acceleration according to Newton's law of gravitation:

$$g = G\frac{m}{r^2} \tag{1}$$

where G is the gravitational constant; g is the gravitational acceleration; m is the mass of the Earth; r is the distance from the Earth's center to the observation point.

When calculating the change in gravitational acceleration at a specific point, the components of gravitational forces explained by the unchanged part of the section cancel each other out:

$$\Delta g(t) = G\frac{\Delta m(t)}{r_n^2} \tag{2}$$

where $\Delta g = g_0 - g_1$; g_0 and g_1 the gravitational acceleration at time moments t_0 and t_1; Δm – the change in the mass of gas in the reservoir; r_n – the distance from the trap's center of mass to the observation point.

Since mass is the product of volume and density, and the reservoir volume is constant, then:

$$\Delta g(t) = G\frac{\Delta \rho(t) V}{r_n^2} \tag{3}$$

where $\Delta\rho = \rho_0 - \rho_1$; ρ_0 and ρ_1 – are the gas densities at time moments t_0 and t_1; V – is the pore volume occupied by the gas in the reservoir.

Let us now consider the change in density in more detail. Injecting carbon dioxide into a reservoir is a complex process with a number of challenges, requiring a thorough examination of numerous factors. First and foremost, it is essential to select a reservoir suitable for the safe storage of carbon dioxide. Under reservoir conditions, CO_2 can exist in various states of matter, depending on temperature and pressure: liquid, gaseous, or supercritical. The state of matter affects the density and viscosity of CO_2, just as temperature and pressure do. Carbon dioxide is heavier than air and, under normal conditions, has a density of 1.98 kg/m^3, a critical temperature of 31 °C, and a critical pressure of 7.38 MPa. The viscosity of CO_2 under reservoir conditions is significantly lower than that of water. With increasing pressure, the solubility of CO_2 in water increases, but does not exceed 0.06 molar fraction. An increase in water salinity is accompanied by a decrease in the solubility of carbon dioxide. An increase in the concentration of carbon monoxide in water leads to an increase in its viscosity. The dissolution of carbon dioxide in water and oil is accompanied by a decrease in temperature. The higher the CO_2 concentration, the more pronounced this temperature effect is. This factor must be taken into account when injecting large volumes, as it can significantly affect the formation of asphaltene-resin-paraffin deposits. The gaseous state of CO_2 corresponds to a wide range of temperatures and pressures. The viscosity is about 10^{-5} Pa·s, the diffusion coefficient is -10^{-5} m^2/s. At temperatures below 31 °C and pressure, CO_2 is in a liquid state. Depending on thermobaric conditions, its density varies from 600 to 1200 kg/m^3. The viscosity is about 10^{-3} Pa·s, the diffusion coefficient is -10^{-9} m^2/s. At pressures above 7.38 MPa and temperatures above 31 °C and higher, CO_2 is in a supercritical state. In the supercritical state of aggregation, CO_2 behaves like a gas-like compressible fluid, but at the same time has a density close to that of a liquid. As the temperature decreases or the pressure increases, the density of CO_2 approaches that of a liquid. At reservoir temperatures and pressures corresponding to the supercritical state, the density of CO_2 varies between 600 and 900 kg/m^3. The viscosity is approximately 10^{-5} -10^{-4} Pa·s, and the diffusion coefficient is -10^{-8} m^2/s. At a pressure of 23 MPa and a temperature of 32 °C, the density of supercritical CO_2 is at its maximum and equals 900 kg/m^3, while the same density in the liquid state of CO_2 is achieved at a pressure of 15 MPa and a temperature of 23 °C. This difference in the required storage pressure for a given density will result in the most significant savings in the power consumption of compressor stations for CO_2 compression if CO_2 is injected in a liquid state. At the same temperature, the viscosity of water will be 16 times greater than that of liquid CO_2 and 30 times greater than that of supercritical CO_2, the density of which is 800-900 kg/m^3, and 48 times greater than the density of gaseous CO_2. This means that liquid CO_2 will displace water more effectively than CO_2 in a gaseous or supercritical state. This will lead to an increase in the reservoir's CO_2 capacity due to a higher displacement efficiency. The diffusion coefficient is highest for CO_2 in a gaseous state, lower for CO_2 in its supercritical state, and lowest for liquid CO_2 [23-27].

Since in the gas regime the volume remains constant, the change in the mass of gases in the reservoir will depend solely on the change in density:

$$\Delta m = V\Delta\rho \tag{4}$$

It is also reasonable to assume that, within the framework of carbon dioxide storage in a depleted reservoir, the change in mass within the reservoir is explained by the injected volumes of carbon dioxide:

$$\Delta m = \rho^{d}_{CO_2}(t)\cdot Q_{CO_2}(t) \tag{5}$$

where, $Q_{CO_2}(t)$ – is the accumulated volume of injected carbon dioxide at time t; $\rho^{d}_{CO_2}(t)$ is the density of carbon dioxide under reservoir conditions.

Then

$$\rho^{d}_{CO_2}(t)\cdot Q_{CO_2}(t) = V(t)\Delta\rho \tag{6}$$

By substituting equation (6) into equation (3), we obtain:

$$\delta g(t) = k\cdot\rho^{d}_{CO_2}(t)\cdot Q_{CO_2}(t) \tag{7}$$

where

$$k = G\frac{1}{r_n^2}$$

As can be seen, the acceleration of gravity depends on the product, $\rho^{d}_{CO_2}(t)\cdot Q_{CO_2}(t)$, these quantities are not separable for gases.

In the gas regime, the coefficient k will remain constant, so the change in gravitational acceleration will depend linearly on the cumulative injection of carbon dioxide. With staged CO_2 injection into the reservoir and gravimetric measurements at control points, the ideal graph of $\delta g(Q_{CO_2}(t))$ will appear as a straight line with a slope equal to the coefficient k (fig. 1, blue line). For gases, $\delta g(Q_{CO_2}(t))$ will depend not on volume, but on the product of the $\delta g(Q_{CO_2}(t))$, $\rho^{d}_{CO_2}$ graph, i.e., on the mass of the injected gas and the density under reservoir conditions. In this regard, the issue of considering the factors influencing the curvature of the $\delta g(Q_{CO_2}(t))$ graph becomes relevant.

It should be noted that the point $\delta g(Q_{CO_2}(0))$ represents the measurements obtained before the start of CO_2 injection and is not affected by the injected carbon dioxide on the overall gravitational field, since the injection has not yet begun.

In real conditions of CO_2 injection into a reservoir, the linear relationship may not necessarily be observed (fig. 1, red line). This raises the question of factors influencing the curvature of the $\delta g(Q_{CO_2}(t))$ graph.

For gases, $\delta g(Q_{CO_2}(t))$ will depend not on volume, but on the product of the $\delta g(Q_{CO_2}(t))\cdot\rho^{d}_{CO_2}$ graph, i.e., on the mass of the injected gas and the density under reservoir conditions. In this regard, the issue of considering the factors influencing the curvature of the $\delta g(Q_{CO_2}(t))$ graph becomes relevant. The product - $\rho^{d}_{CO_2}(t)\cdot Q_{CO_2}(t)$ can be transformed using the Mendeleev-Clapeyron equation for gases, since the gas density itself under reservoir thermodynamic conditions depends on the volume of injected gas. However, in this case, we will also obtain the same result, since δg depends on the mass of the injected gas.

First, low-permeability reservoirs should be considered. If gravitational acceleration measurements are taken at a distance from the wells, the delayed spread of carbon dioxide within the reservoir reduces the impact of fluid changes on gravitational acceleration, and the δg values for the corresponding $Q_{CO_2}(t)$ values will be underestimated. At the same time, when performing gravimetric measurements near the wells in low-permeability reservoirs, δg readings may be overestimated due to the compaction of injected CO_2 that has not yet spread throughout the formation. In other words, the readings are influenced by the rate at which the fluid compacts within the reservoir.

Therefore, to ensure that gravimetric data are most representative, measurements should be conducted when the reservoir has reached a stable regime. If gravimetric readings deviate from a linear relationship, it is recommended to conduct repeated gravimetric measurements without further CO_2 injection. The frequency of measurements depends on the permeability of the reservoir. If readings over time begin to return to the linear trend, this indicates that CO_2 is spreading successfully and equilibrium is being restored in the reservoir. This approach helps prevent abnormal pressure increases in the reservoir caused by delayed CO_2 migration. Without identifying pressure increases, there is a high risk of compromising the integrity of older well casings.

The compaction rate can be influenced not only by reservoir permeability, as under real conditions the reservoir regime may not be purely gas-filled but may also be water-driven. All the dependencies described above are disrupted under a water-drive regime; however, the $\delta g(Q_{CO_2}(t))$ graph can still indicate a shift from a gas regime to a water-drive regime. If during gravimetric monitoring the $\delta g(Q_{CO_2}(t))$ curve at some stage deviates toward the abscissa, it can be assumed that the medium is compacting more slowly due to an increase in reservoir volume. Continued CO_2 injection

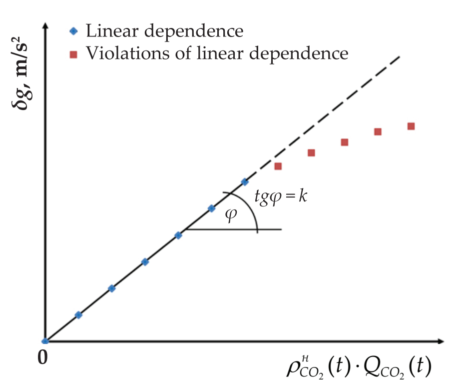

Fig. 1. Hypothetical graph of $\delta g(Q_{CO_2}(t))$

increases the volume of the reservoir and begins to displace underlying formation water [22]. Excess water starts to redistribute along the formation, but along the axis coinciding with the direction of gravitational acceleration, the total mass of the overlying strata decreases due to replacement of denser water by less dense CO_2. Theoretically, this does not exclude an increase in gas density in the reservoir, but the compaction rate of the medium (in a water-drive regime it is more accurate to refer of the density of the medium rather than the gas) decreases, which is reflected in the $\delta g(Q_{CO_2}(t))$ graph as a reduction in the slope.

Conversely, a curvature of the $\delta g(Q_{CO_2}(t))$ graph toward the ordinate may indicate an increase in the compaction rate, which could result from a decrease in reservoir volume, a rise in the gas-water contact (GWC), or partial water influx into the reservoir. However, explaining this through reservoir processes is difficult due to the increasing gas volume in the reservoir, which counteracts GWC rise. Therefore, deviation toward the ordinate is unlikely. The only possible explanation would be excessive activity of formation water in the aquifer during the gravimetric monitoring period.

Thus, the causes of $\delta g(Q_{CO_2}(t))$ graph curvature can include low reservoir permeability and changes in the GWC.

The cause can be identified through repeated gravimetric surveys without further CO_2 injection. If in a low-permeability reservoir the readings gradually return to a linear trend, whereas GWC changes due to water displacement by CO_2 would not revert even in a high-permeability reservoir, this allows determination of the reason for deviation from linearity in $\delta g(Q_{CO_2}(t))$.

When considering real CO_2 injection conditions, it is necessary to account for assumptions regarding fluid density changes in the reservoir. The value $\Delta\rho$ represents the change in density, describing the fluid mixture under the assumption of uniform distribution of CO_2 and natural gas throughout the pore volume. However, the molar mass and density of carbon dioxide under standard conditions are higher than those of natural gas, which in most cases consists predominantly of lighter methane. Consequently, it is likely that under equilibrium in the CO_2 reservoir, especially at high formation pressures where CO_2 is closer to a liquid state than a gaseous one (fig. 2), gravitational forces will redistribute CO_2 toward the lower part of the structural trap, while natural gas will rise upward.

In this case, the masses of gases, compared to a uniform distribution throughout the reservoir pore volume, will not change, provided that the injected volumes of carbon dioxide are appropriate. However, the value r, related to the distance of elementary gas volumes from the observation point, will vary, which may lead to differences in the measured changes in gravitational acceleration compared to a uniform gas distribution in the pore volume [28]. Nevertheless, if for CO_2 the distance of elementary volumes from the measurement point increases, for natural gas this distance will decrease. In this case, it can be assumed that there is a mutual compensation of gravitational field components related to the gravitational redistribution of CO_2 and natural gas separately. However, the question of whether this compensation allows $\Delta\rho$ in a uniform gas distribution to be considered equivalent to the same quantity during the gravitational settling of CO_2 and rise of natural gas in the reservoir remains open.

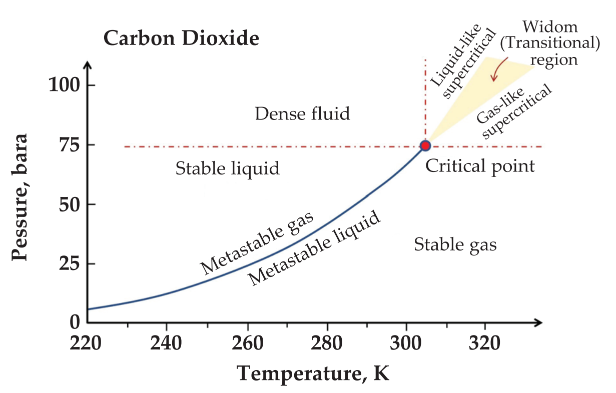

Fig. 2. CO_2 phase transition diagram

The issue of fluid redistribution in reservoirs containing not only gas but also oil or condensate also remains unresolved [29-33]. Complex multi-fluid systems, where oil, being lighter than water, can under the influence of gravity be both below and above carbon dioxide - which can reach a density of 800 kg/m³ at a temperature of 330 K and a pressure of 255 kgf/cm² - pose particular challenges. At the same time, condensate at varying pressures may either precipitate or vaporize, mixing with natural gas. For each stage of CO_2 injection, different vertical fluid arrangements may form within the reservoir, necessitating additional geophysical investigations along the observation wellbores. Among the existing GIS-based methods, those capable of highlighting differences in the molecular composition of the fluid even in cased wellbores, as well as high-frequency induction logging with isoparametric probing in wells cased with fiberglass tubing, may be suitable for addressing this task [34, 35].

Regarding qualitative interpretation of gravimetric monitoring data, it is worth noting the potential to detect the risk of CO_2 reaching the closure contour of the trap using this method. In water-drive reservoirs, to monitor the spread of CO_2, data on changes in gravitational acceleration from control points across the study area can be combined to construct an isoline map. By overlaying the δg isoline map onto the structural contour map of the reservoir top and marking the closure contour, and then sequentially updating the δg isoline maps over time, the dynamics of CO_2 propagation throughout the reservoir can be tracked. Undisturbed portions of the reservoir filled with water will show δg readings of zero, whereas areas where water is displaced by CO_2 will exhibit negative δg values. By monitoring CO_2 spread via gravimetric measurements, injection can be halted in time to prevent lateral migration of carbon dioxide within the structural trap (fig. 3).

As can be seen from figure 3, a linear dependence is also observed in the areal version of the distribution of the acceleration of gravity, where the plan reflects the isohypses (terrain height) and isolines δg at different observation points at a certain point in time and without violating linearity.

For a gas-mode reservoir, in any case – even if all assumptions are violated – it is still permissible to construct δg isoline maps. The gravitational field will change regardless, due to alterations in the reservoir properties, which will be reflected in gravimetric survey readings in one form or another. This confirms the potential of gravimetric monitoring during CO_2 injection into a depleted hydrocarbon reservoir.

It should be noted that before conducting gravimetric surveys at any site, the instrumentation issues must be addressed. Gravimetry can be conducted using satellites, which allows automation of the survey process. Nevertheless, the accuracy of gravitational anomaly measurements determines the range of targets where CO_2 injection can be monitored using this method: the higher the measurement accuracy, the smaller the volumes of injected CO_2 that can be detected, and the wider the variety of injection sites available for study. Therefore, when selecting instrumentation, preference should be given to high-precision gravimeters used in terrestrial surveys [4–12].

The Canadian-made CG-5 Autograv gravimeter meets these requirements. This instrument has undergone various technical improvements and studies related to the influence of external factors on its measurements. The impact of humidity, ambient temperature, and other factors on the CG-5 Autograv readings has been investigated. The sensitivity of the sensor of this model of the Autograv CG-5 gravimeter to changes in gravity is 1 mGal [23-27, 36]. Regardless of the chosen gravimeter, ideally it should include automatic corrections for external factors, which, in addition to climatic conditions, include the time of day, the position of the Moon relative to the Earth, and its effect on gravitational acceleration. If such corrections are not present in the instrument, the gravimeter should be accompanied by scientific studies assessing the influence of external factors on its readings [4-12].

The frequency of gravimetric measurements depends not only on the precision of the gravimetric equipment but also on the depth of the structural trap and the rate of CO_2 injection [37]. The change in gravitational acceleration for a given injected CO_2 volume must exceed the measurement error of the gravimeter. For example, with a measurement error of 10^{-9} m/s^2 (0.1 mGal), for a structural trap at a depth of 1000 m, the minimum detectable injected CO_2 volume is 15000 t, while at a depth of 3000 m it is 135000 t.

The sensitivity of the Autograv CG-5 gravimeter sensor to changes in gravity is 0.001 mGal. The root-mean-square measurement error on the stand in stationary mode, characterizing the repeatability of readings, is 0.005 mGal. During field measurements with the same gravimeter at the same points with a distance between points of 2.5-5 m, the repeatability of readings was within the limits specified by the manufacturer, i.e., the root-mean-square error did not exceed ±0.005 mGal [28, 36, 38]. Currently, ground-based gravimetric surveys have errors lying in the range from 0.05 to 0.1 mGal [23, 24, 36, 38]. Field tests have also shown that the difference between individual measurements and the average for a CG-5 Autograv gravimeter station does not exceed 0.005 mGal. With a measurement error of 10^{-9} m/s^2 (0.1 mGal), if the structural trap is located at a depth of 1000 m, the minimum injected volume of CO_2 would be 15000 tons, and at a depth of 3000 m, 135000 tons.

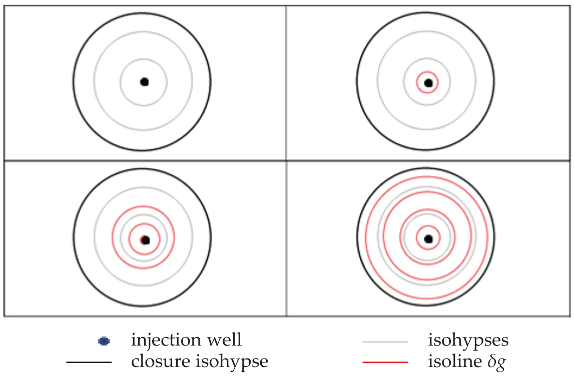

Fig. 3. Scheme of the distribution of changes in gravitational acceleration in a hypothetical structural anticlinal trap

The proposed approach—monitoring the distribution of carbon dioxide in geological structures using gravimetry (constructing a δg contour map) – allows for tracking the current state of the deposit (reservoir) into which CO_2 is injected, monitoring the tightness of old production gas wells used for injection, and monitoring the distribution of carbon dioxide in their area [34, 35, 37]. Using the $\delta g(Q_{CO_2}(t))$ dependence graph allows us to timely record a decrease in the rate of local spread of carbon dioxide and prevent its movement beyond the closure isohypse.

Conclusions

1. Additional revenue from CO_2 utilization, considered as a reduction in greenhouse gas emissions, can be obtained within the framework of economic mechanisms of international conventions and post-Kyoto limitations.
2. Gravimetric monitoring of CO_2 distribution in geological structures aims to minimize potential risks and increase the efficiency of implemented projects.The proposed idea of using the capabilities of gravimetry to monitor the distribution of CO_2 in geological structures is the author's approach and may cause further discussion.
3. The techno-economic efficiency of CO_2 distribution monitoring in geological structures using gravimetry (gravimetric survey) is determined by the ability to study the Earth's gravitational field, which reflects the density distribution of the rocks forming the structures. This allows identifying structures hidden by sedimentary layers and inaccessible to conventional geological methods, determining the conditions and elements of anomalous objects based on local gravity anomalies, and accounting for the influence of overlying masses during borehole gravimetric measurements.
4. A comparison of geological and gravimetric data shows that there may be a direct correlation between gravimetric anomalies and known geological objects, indicating the identity of geological structures and sources of the gravitational field, or an indirect correlation linking field features with geological elements.

5. The reliability of interpretation depends on the completeness and accuracy of a priori information: geological and petrophysical data, drilling data, and other geophysical methods.
6. Injection of carbon dioxide into a reservoir initially saturated with a lower-density formation fluid may activate gas-dynamic risks; therefore, one of the key issues is the distribution and rate of CO_2 spread throughout the volume of the natural trap.
7. Gravimetric monitoring allows tracking the current state of the geological structure where CO_2 injection is conducted and timely strengthening the integrity control of old wells in zones affected by CO_2 distribution.
8. Constructing δg isoline maps provides control over the spread of CO_2 in depleted gas reservoirs and aquifers under gas and water-drive regimes.
9. The proposed $\delta g(Q_{CO_2}(t))$ dependence graph makes it possible to promptly detect a reduction in the local CO_2 propagation rate and prevent CO_2 from escaping beyond the closure contour of the trap.

References

1. Gasumov, R. A., Gasumov, E. R. (2025). On the selection of an aquifer as an absorbing reservoir for the disposal of industrial wastewater. *Nauka Innovatsii Tekhnologii*, 1, 149-176.

2. Gasumov, R. A., Gasumov, E. R. (2025). Assessment of the impact of underground disposal of liquid waste on a geological environment (using the example of depleted gas fields). *South of Russia: Ecology, Development*, 20(1), 145-159.

3. Nazirova, A. B. (2018). Methods for assessing gravity anomalies in oil and gas fields using information technologies. *Bulletin of the Kazakh-British Technical University*, 15(3), 118-128.

4. Grushinsky, N. P., Sazhina, N. B. (1981). Gravity exploration. *Moscow: Nedra.*

5. Andreev, O. P., Kobylkin, D. N., Akhmedsafin, S. K., et al. (2012). Gravimetric monitoring of gas and gas condensate field development. Status, problems, prospects. *Moscow: Nedra.*

6. Serkerov, S. A. (2006). Gravity and magnetic exploration in the oil and gas industry. *Moscow: Neft i Gaz.*

7. Azarov, S. S., Prishivalko, N. I. (2002). Results of repeated gravimetric observations of an exploited gas deposit. *Exploration Geophysics*, 39, 97-101.

8. Lozhevsky, M. I., Mikhailov, I. N., Rosenberg, V. N., Chertovskikh, K. A. (2002). Gravimetric control in the development of hydrocarbon fields and operation of underground gas storage facilities. *Exploration and Protection of Subsoil*, 2, 23-26.

9. Lozhevsky, M. I., Mikhailov, I. N., Chertovskikh, K. A. (2002). Possibilities of gravity exploration in the search for and study of underground structures. *Exploration and Protection of Subsoil*, 2, 38-41.

10. Pugin, A. V. (2019). Gravity exploration. *Perm: Perm State National Research University.*

11. Soromotin, A. V., Lekomtsev, A. V., Ilyushin, P. Yu. (2022). Analysis of the features of the application of CO_2 HUFT-N-PUFF technology. *Bulletin of the Tomsk Polytechnic University. Engineering of Georesources*, 333(12), 178-189.

12. Liu, S.-Y., Ren, B., Li, H.-Y., et al. (2022). CO2 storage with enhanced gas recovery (CSERG): A review of experimental and numerical studies. *Petroleum Science*, 19(2), 594-607.

13. Cui, G., Pei, S., Rui, Z., et al. (2020). Whole process analysis of geothermal exploitation and power generation from a depleted high-temperature gas reservoir by recycling CO_2. *Energy*, 217, 119340.

14. Vandeweijer, V., Hofstee, C., Pelt, W.V., Graven, H. (2021). CO2 injection at K12-B, the final story. In: *15th Inernational Conference on Greenhouse gas control technologies, GHGT-15, Abu Dhabi, UAE, March.*

15. Fan, L., Tan, Q., Li, H., et al. (2021). Simulation on effects of injection parameters on CO_2 enhanced gas recovery in a heterogeneous natural gas reservoir. *Advanced Theory and Simulations*, 4, 2100127.

16. Osipov, A. V., Mustaev, R. N., Monakova, A. S., et al. (2020). Mechanisms and options for utilization and burial of carbon dioxide in the subsoil. *Scientific and Methodological Journal. Geology and Exploration*, 64(4), 40-53.

17. Dymochkina, M. G., Samodurov, M. S., Pavlov, V. A., et al. (2021). Geological potential for carbon dioxide capture and storage in the Russian Federation. *Oil Industry*, 12, 20-23.

18. Dmitrievsky, A. N., Khan, S. A., Dorokhin, V. G. (2023). Geological repository of carbon dioxide. Theory, history and methodology. *Moscow: Publishing House «FLINTA».*

19. Mikhailovsky, A. A. (2022). Formation gas losses at UGS in aquifers. *Georesources*, 24(3), 182-186.

20. Popova, I. M., Kolmar, O. I. (2023). Low-carbon development of Russia: challenges and opportunities in the new conditions. *Bulletin of International Organizations*, 18(4), 62-95.

21. Kalacheva, L. P., Ivanova, I. K., Portnyagin, A. S., et al. (2023). Assessment of the possibility of burying carbon dioxide in a hydrated state in subpermafrost aquifers of the Vilyui syneclise. *Oil and Gas Geology. Theory and Practice*, 18(4).

22. Novikov, D. A., Fomina, Ya. V., Yurchik, I. I., et al. (2023). First experience in zonal forecast over the Moscow artesian basin for implementation of CCS projects. *Bulletin of Tomsk Polytechnic University. Georesources Engineering*, 334(10), 119-139.

23. Abramov, D. V., Koneshov, V. N., Chebrov, V. N. (2016). Improving the methodology of long-term observations with the CG-5 relative gravimeter. *Seismic Instruments*, 52(3), 20-26.

24. Yetirmishli, G. J., Kazimova, S. E., Gadirov, Z. S. (2025). Investigation of the deep structure of the earth's crust of Azerbaijan and the Caspian region using the method of seismic tomography. *SOCAR Proceedings*, 3, 16-30.

25. Drobyshev, M. N., Koneshov, V. N., Abramov, D. V., Malysheva, D. A. (2021). Improving the Accuracy of Gravimetric Observations Using Seismic Information. *Geophysical Research*, 22(3), 26-34.

26. Ermolayev, A. I., Efimov, S. I., Pyatibratov, P., Minikhanov, E. D. (2023). Estimation of the maximum downhole pressure, excluding the destruction of the bottom-hole zone of the formation, based on geomechanical core studies. *SOCAR Proceedings*, SI1, 61-69.

27. Molev, V. P. (2019). Methodology and technology of ground-based gravimetric surveys. *Vladivostok: Far Eastern Federal University.*

28. Osipov, A. V., Mustaev, R. N., Monakova, A. S., et al. (2022). Mechanisms and options for utilization and disposal of carbon dioxide in the subsoil. *Bulletin of Higher Educational Institutions. Geology and Exploration*, 4, 40-53.

29. Shchergina, E. A., Smetanin, A. B., Shchergin, V. G. (2022). Analytical review of the mechanisms of formation of deposits with inclined hydrocarbon contacts. *Geology of Oil and Gas*, 1, 31-47.

30. Gasumov, E. R., Gasumov, R. A. (2025). Impact of injection of industrial liquid waste on hydrodynamic conditions of receiving horizon. *Bulletin of the Tomsk Polytechnic University Geo Assets Engineering*, 335(5), 37-48.

31. Gasumov, E. R., Gasumov, R. A. (2024). Estimation of the hydrodynamic perfection of the well-reservoir system at the stage of opening a productive reservoir. *Geology and Geophysics of Russian South*, 14(4), 152-165.

32. Gasumov, R. A., Gasumov, E. R., Valiev, V. M., Musaeva, F. (2024). Geological and technical-economic issues of designing underground gas storage facilities in reservoir formations. *Geology and Geophysics of Russian South*, 14(4), 152-165.

33. Koneshov, V. N., Abramov, D. V., Drobyshev, N. V., Malysheva, D. A. (2023). Assessment of the influence of humidity on long-term high-precision measurements with the CG5 Autograv gravimeter. *Geophysical Research*, 24(2), 87-94.

34. Gasumov, E., Veliyev, V., Gasumov, R., Suleymanov, G. (2024). Technical and economic aspects of reducing carbon dioxide emissions into the atmosphere. *Reliability: Theory & Applications*, 6(81), 2(19), 930-937.

35. Los, A. S., Korolkov, V. K. (2023). Conditions for carbon dioxide disposal in an aquifer with further geophysical control. In: Proceedings «Innovative technologies in the oil and gas industry. Problems of sustainable development of territories».

36. Belyaev, A. S., Rozenberg, V. N. (2016). The influence of measurement methodology on the results of high-precision gravimetric survey. *Exploration Geophysics*, 93, 129-133.

37. Gasumov, R. A., Gasumov, E. R., Veliev, V. M., et al. (2022). Development of a three- dimensional geological model of the upper control horizons and near-surface sediments for investigation of the system of monitoring the tightness of the underground storage. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 333(6), 86–95.

38. Drobyshev, M. N., Koneshov, V. N. (2013). Estimation of the ultimate accuracy of the CG-5 Autograv Gravimeter. *Seismic Instruments*, 49(2), 39-43.