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Experimental validation of enhanced oil recovery methods at the Nasiriyah field

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Abstract. This article presents a program of key laboratory studies required for experimental verification of a predictive model for enhanced oil recovery at the Nasiriyah field (Iraq, Cretaceous Mishrif formation). Previously performed numerical modeling demonstrated that injection of fractionated natural gas enriched with C3–C4 components (liquefied petroleum gases) can achieve miscible oil displacement under reservoir conditions of *P* = 25 MPa, *T* = 95°C. However, a comprehensive experimental verification is required to transition from predictive calculations to a technologically sound solution. The proposed program includes three interrelated blocks: 1) pressure–volume–temperature (PVT) studies of reservoir oil – verification of thermodynamic properties, calibration of the Peng–Robinson equation of state, and determination of swelling factors upon contact with gas agents; 2) determination of minimum miscibility pressure by the slim-tube method for raw associated gas, enriched mixture (60% C1 + 40% C3–C4), and liquefied petroleum gases; 3) core flooding experiments on core samples from the Mishrif formation – comparison of continuous gas injection and water-alternating gas flooding. The expected results enable calibration of the reservoir simulation model, justification of the optimal gas agent and injection mode, as well as preparation of a feasibility study for the industrial implementation at the Nasiriyah field and similar carbonate reservoirs in Southern Iraq.

Keywords: enhanced oil recovery, pressure–volume–temperature (PVT) studies, minimum miscibility pressure, slim-tube, core flooding experiments, water-alternating gas injection, fractionated natural gas, carbonate reservoir, Nasiriyah field

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Экспериментальное подтверждение методов повышения нефтеотдачи на месторождении Насирия

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Резюме. В данной статье представлена программа ключевых лабораторных исследований, необходимых для экспериментального подтверждения прогнозной модели повышения нефтеотдачи пластов на месторождении Насирия (Ирак, меловая формация Мишриф). Ранее выполненное численное моделирование показало, что закачка фракционированного природного газа, обогащенного компонентами С3–С4 (сжиженные углеводородные газы), способна обеспечить смешение, вытеснение нефти при пластовых условиях: *P* = 25 МПа, *T* = 95 °С. Однако для перехода от прогнозных расчетов к технологически обоснованному решению требуется комплексная экспериментальная верификация. Предлагаемая программа включает три взаимосвязанных блока: 1) PVT-исследования пластовой нефти – верификация термодинамических свойств, калибровка уравнения состояния Пенга – Робинсона и определение факторов набухания при контакте с газовыми агентами; 2) определение минимального давления смешиваемости методом slim-tube для сырого попутного газа, обогащенной смеси (60 % С1 + 40 % С3–С4) и сжиженных углеводородных газов; 3) фильтрационные эксперименты на керновых образцах формации Мишриф – сравнение непрерывной газовой закачки и водогазового воздействия. Ожидаемые результаты позволяют калибровать гидродинамическую модель, обосновать выбор оптимального газового агента и режима закачки, а также подготовить технико-экономическое обоснование для промышленного внедрения технологии на месторождении Насирия и аналогичных карбонатных коллекторах Южного Ирака.

Ключевые слова: повышение нефтеотдачи, PVT-исследования, минимальное давление смешиваемости, slim-tube, фильтрационные эксперименты, водогазовое воздействие, фракционированный природный газ, карбонатный коллектор, месторождение Насирия

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Introduction

The Nasiriyah field, located in Dhi Qar Province in southern Iraq, is one of the largest undeveloped oil fields in the country, with geological reserves estimated at approximately 4.4 billion barrels of oil. The main productive horizon is the Cretaceous Mishrif formation (Upper Maastrichtian–Campanian), which represents a complex carbonate reservoir characterized by high lateral and vertical heterogeneity. The reservoir oil is characterized by relatively low viscosity (1.8 mPa×s at 95°C) and moderate density (780 kg/m³), making it a promising target for the application of enhanced oil recovery (EOR) methods, primarily gas-based techniques [1, 2].

In previous studies by the authors, numerical simulation of oil displacement from the Mishrif formation using various gas agents was performed with a compositional reservoir simulator. The simulation results demonstrated that injection of fractionated natural gas enriched with C3–C4 components of liquefied petroleum gases (LPG) enables miscible displacement at reservoir pressure of 25 MPa and temperature of 95°C. The oil recovery factor can thereby be increased by 15–25% compared to the baseline waterflooding scenario [3, 4]. Furthermore, simulation of water-alternating gas (WAG) flooding demonstrated the potential for additional enhancement of the oil recovery factor by improving the areal and vertical sweep efficiency [5].

Despite the encouraging results of numerical simulation, the transition from predictive calculations to a technologically sound industrial implementation project requires comprehensive experimental verification. Numerical models based on equations of state (in particular, the Peng–Robinson equation) contain a number of assumptions and approximations that must be validated with laboratory data. Key uncertainties include: the accuracy of the phase behavior description for the "reservoir oil–gas agent" system, the minimum miscibility pressure (MMP) for specific types of injected gas, and the effect of carbonate reservoir micro-heterogeneity on displacement efficiency [6–8].

Numerical simulation of EOR processes, despite its widespread application and continuous improvement of software packages, has a number of fundamental limitations. The main limitation is the necessity to use thermodynamic equations of state (EOS) to describe the phase behavior of multicomponent hydrocarbon systems. The Peng–Robinson equation, widely used in the petroleum industry, provides an adequate description of phase equilibrium for most hydrocarbon systems. Nevertheless, its application requires mandatory calibration based on experimental pressure–volume–temperature (PVT) data for each specific reservoir oil [1, 3].

Modeling of miscible displacement processes, particularly in carbonate reservoirs, is associated with significant methodological difficulties. The carbonate rocks of the Mishrif formation are characterized by the presence of fractures of various scales, vugular formations, and complex intergranular porosity. This leads to the formation of a system with dual porosity and dual permeability. Accurate description of mass transfer between the matrix and fractures during gas displacement requires adaptation of models based on core flooding experimental data on natural core samples [2, 9]. Furthermore, upon contact of reservoir oil with gas agents containing light hydrocarbon components (C1, C3–C4), there is a possibility of asphaltene precipitation. This phenomenon, in turn, can lead to deterioration of the reservoir's flow characteristics. This risk cannot be reliably assessed by numerical methods alone and requires experimental validation [10].

International practice in EOR project design, governed by the standards of the Society of Petroleum Engineers (SPE), mandates the performance of a comprehensive set of laboratory studies prior to making a decision on industrial technology implementation. According to SPE recommendations, the minimum required scope includes PVT studies of reservoir oil and injected agents, MMP determination, and core flooding experiments on core material [11]. Practical experience from miscible gas injection projects at major carbonate fields in the Middle East confirms the high efficiency of this method when pressure is maintained above the MMP and gas breakthrough is controlled [12]. A review of CO_2-EOR methods in carbonate reservoirs indicates that the efficiency of miscible and immiscible displacement processes is determined by a combination of factors, including the petrophysical properties of the reservoir, thermodynamic conditions, and the type of injected agent [13]. The methodology of slim-tube tests for MMP determination is regulated by international standards, which provide for testing at a series of pressures with temperature and displacement rate control [14]. Practical recommendations for core flooding experiments in WAG projects include optimization of the water-gas slug ratio, displacement rate, and temperature conditions [15]. For carbonate reservoirs characterized by complex pore structure and a high degree of fracturing, this set of studies becomes particularly important [9, 10]. For Cretaceous carbonate reservoirs of the Middle East (Mishrif, Yamama, Asmari formations, etc.), international experience in gas EOR project implementation demonstrates the need for an extended research scope. In particular, for miscible displacement projects, it is recommended to conduct multiple contact miscibility (MCM) tests and to study the effect of injection rate on the displacement factor [7, 8, 10].

The cost of the comprehensive laboratory research program (PVT + slim-tube + core flooding experiments) for a single field is estimated by various sources at between 200,000 and 500,000 USD, depending on the scope of studies and the number of gas agents tested. At the same time, the cost of drilling a single injection well at the Nasiriyah field is estimated at 5–10 million USD, while the cost of the full scope of field-scale activities amounts to hundreds of millions of dollars. Thus, laboratory research costs account for less than 1% of the total capital expenditures for EOR project implementation, while significantly reducing the risks of making incorrect technological decisions [15, 16]. Indirect benefits from conducting laboratory studies should also be taken into account: the results of PVT studies and miscibility tests can be used to calibrate simulators applicable to other fields in Southern Iraq with similar geological and physical conditions [3, 16].

The objective of this work is to develop a comprehensive program of key laboratory studies required for experimental verification of the predictive EOR model for the Nasiriyah field (Iraq, Mishrif formation). The program covers three interrelated research directions, each addressing specific tasks, but collectively ensuring complete verification of the predictive gas EOR model.

The first direction includes PVT studies of reservoir oil aimed at obtaining reliable thermodynamic characteristics and calibrating the Peng–Robinson equation of state. The second direction provides for MMP determination by the slim-tube method for three types of gas agents. The third direction consists of conducting core flooding experiments on core samples from the Mishrif formation to evaluate the displacement factor under various gas injection modes.

The research program provides for testing three types of gas agents: raw associated gas, enriched mixture (60% C1 + 40% C3–C4), and LPG (C3–C4). Implementation of this program will enable the transition from qualitative predictions to quantitatively substantiated technological solutions, calibrate the reservoir simulation model, justify the selection of the optimal gas agent and injection mode, and prepare a feasibility study for industrial implementation of the technology at the Nasiriyah field and similar carbonate reservoirs in Southern Iraq [16].

Materials and methods

Object of study. The object of study is the Cretaceous Mishrif formation of the Nasiriyah field, located in Dhi Qar Province in southern Iraq. The field is one of the largest undeveloped oil fields in the country, with geological reserves of about 4.4 billion barrels, and is at a late stage of development. As of January 1, 2024, 23 wells have been drilled (15 producers, 5 injectors, 3 observation wells). The primary development mode is waterflooding. The current oil recovery factor is 22.4% of the initial geological reserves, which is due to the high heterogeneity of the carbonate reservoir (fracturing, vugularity) and premature water breakthroughs. The low oil recovery factor confirms the high potential for the application of gas-based enhanced oil recovery methods. The Mishrif formation (Upper Maastrichtian–Campanian) is a complex carbonate reservoir with high lateral and vertical heterogeneity, characterized by dual porosity and dual permeability due to the presence of fractures of various scales and vugs [2, 4].

Reservoir conditions of the field: reservoir pressure – 25 MPa, reservoir temperature – 95°C. The reservoir oil is characterized by a density of 780 kg/m³, viscosity of 1.8 mPa×s at reservoir temperature, saturation pressure of 15.2 MPa, gas content of 95 m³/m³, and formation volume factor of 1.42. The productive interval is represented by various lithotypes of carbonate rocks, including shallow-water reef limestones, foraminiferal packstones and grainstones, with porosity of 12–25% and gas permeability of 1–100 mD. This study uses data from 5 key production wells (Ns-15, Ns-23, Ns-41, Ns-57, Ns-82) located in different structural blocks of the field. Reservoir simulation was performed on a sector model including 5 existing production wells and 3 planned injection wells [1, 5, 6].

PVT studies. For PVT studies, representative samples of reservoir oil are required, taken in accordance with standard procedures ensuring the preservation of thermobaric conditions and sample composition. It is recommended to collect at least three single-zone samples from wells located in different areas of the field to account for lateral variability of oil properties. Samples should be taken at the reservoir depth using bottom-hole samplers at a pressure not lower than the saturation pressure of 15.2 MPa. After delivery of samples to the laboratory, sample quality verification should be performed by measuring the pressure in the receiving vessels and comparing it with the reservoir pressure of 25 MPa. The component composition of each sample should be determined by gas chromatography in accordance with ASTM D86 standard [1, 2].

For conducting PVT studies, a PVT apparatus capable of operating at pressures up to 70 MPa and temperatures up to 150°C is required, covering the range of reservoir conditions of the Nasiriyah field (P = 25 MPa, T = 95°C). The apparatus should include a sight glass cell with a magnetic stirrer to ensure phase equilibrium, a precise volume measurement system (accuracy not less than 0.01 cm³), a capillary viscometer for determining viscosity at high pressures and temperatures, and a gas chromatography system for determining the component composition of phases. Recommended PVT equipment manufacturers include Chandler Engineering (model 3000GL), DBR (model PVT-2000), or EQUI-PVT (RUSKA series). All systems must be calibrated and certified in accordance with the requirements of GOST ISO/IEC17025-2019[1] [1, 14].

The PVT experimental program includes the following stages:

1) Separator tests – determination of oil and gas properties under standard separation conditions;

2) Differential liberation – construction of curves showing changes in oil properties with stepwise pressure reduction from reservoir to atmospheric;

3) Swelling tests – three series of experiments with different gas agents (raw gas, enriched mixture, LPG); in each series, gas is sequentially added to oil in several steps at a constant pressure of 25 MPa, recording changes in saturation pressure, formation volume factor, viscosity, and swelling factor;

[1] ISO/IEC 17025:2017. *General requirements for the competence of testing and calibration laboratories.* Moscow: Standartinform; 2021, 32 p.

4) Calibration of the Peng–Robinson equation of state using experimental data [1, 6].

Minimum miscibility pressure determination by the slim-tube method. MMP is defined as the minimum pressure at which the injected gas and reservoir oil can achieve complete miscibility through multiple contact miscibility (MCM). At pressures above the MMP, the interfacial tension between the phases approaches zero, and the displacement efficiency reaches its maximum value. The slim-tube method (displacement tube) is the most widely applied experimental method for MMP determination, as confirmed by a systematic review of ten experimental methods, in which slim-tube and core flood tests were recognized as the most reliable approaches [17]. Alongside the classical slim-tube, new methods for MMP determination have been proposed in recent years, in particular the fluid method, which demonstrates high convergence with the results of traditional slim-tube tests [18]. The method is based on displacing oil by gas from a long narrow tube packed with sand or glass microspheres at various pressures. The MMP is determined as the pressure at which a sharp increase in displacement efficiency is observed (typically above 90–95% at 1.2 pore volumes of injected gas) [6, 7, 14].

The slim-tube apparatus consists of the following main components:

1) A spiral stainless steel tube 12–18 m in length with an internal diameter of 6.35 mm (¼ inch), packed with quartz sand of 160–200 mesh or glass microspheres 60–80 μm in diameter;

2) A temperature control system with an accuracy of ±0.1°C over a range up to 150°C (air bath or liquid bath);

3) Positive displacement pumps for oil and gas delivery with adjustable injection rate;

4) A back-pressure regulator system with an accuracy of ±0.01 MPa;

5) A gas flow meter and liquid collector for measuring the volume of displaced oil [7, 14].

In the experimental plan, tests will be conducted at a constant temperature of 95°C, corresponding to reservoir conditions. The pressure range varies from 15 to 40 MPa with increments of 2–3 MPa for each gas agent under investigation.

The test protocol includes the following steps:

1. Preparation of the experimental tube, including cleaning, drying, packing with sand, and subsequent determination of porosity and permeability.

2. Saturation of the tube with reservoir oil under reservoir-simulating conditions, followed by exposure to achieve thermodynamic equilibrium.

3. Displacement of oil by the selected gas agent at the set pressure and a constant injection rate of 0.1–0.2 mL/min.

4. Recording of the volume of displaced oil after injection of each interval of 0.1 pore volume of gas.

5. Repetition of the tests at the next pressure value.

To ensure high reproducibility of the experimental data, the system is calibrated using a reference oil sample before each test series. Temperature control is continuously monitored by at least three thermocouples.

To improve the accuracy of MMP determination, it is advisable to combine slim-tube tests with interfacial tension (IFT) measurements. This approach allows additional verification of the results, as also confirmed by literature data [19]. For each gas agent, at least 6–8 tests at different pressures are planned [6, 7, 14].

Core flooding experiments. For core flooding experiments, core samples from the Mishrif formation are used, taken from the productive interval of the Nasiriyah field. The recommended volume of core material is at least 10 cylindrical plugs with a diameter of 30–38 mm and a length of 60–80 mm. The samples should be taken from various lithotypes of the Mishrif formation, including shallow-water reef limestones, foraminiferal packstones and grainstones. Core sample preparation includes:

– cleaning from drilling mud and salts by sequential flushing with tetrahydrofuran and methanol;

– drying at 105°C to constant weight;

– determination of basic petrophysical properties (porosity by helium porosimeter, absolute gas permeability, capillary pressure);

– restoration of saturation with model reservoir water and oil.

Target parameters:

– porosity ranges from 12 to 25%,

– gas permeability is in the range of 1–100 mD [2, 4, 15].

Core flooding experiments are conducted on a specialized facility – a core flooding system capable of operating under reservoir conditions. The system includes the following key components: a high-pressure core holder designed for working pressures up to 70 MPa and temperatures up to 150°C, with the capability of maintaining a confining pressure exceeding the pore pressure by 2–3 MPa. Also provided are positive displacement pumps for accurate delivery of oil, gas and water, including a heating system ensuring a stable temperature of 95°C. For process monitoring, differential pressure transducers with a measurement accuracy of ±0.001 MPa are used. Separation of produced fluids (oil, water and gas) is performed by a separator, and the entire experimental process is controlled and recorded by a data acquisition and processing system. This facility enables studies in two main displacement modes: continuous gas injection (CGI) and WAG flooding. For the WAG mode, switching valves are used to alternate water and gas injection with a prescribed slug ratio of 0.5:1 to 1:1 (water:gas) by volume [5, 15].

The core flooding experimental program includes four experimental scenarios:

1) Continuous injection of LPG at a pressure above the MMP (30 MPa) – to assess the maximum potential of miscible displacement;

2) Continuous injection of enriched mixture 1 at a pressure of 30 MPa – to assess the efficiency of miscible displacement with a less enriched agent;

3) Continuous injection of raw gas at a pressure of 20 MPa (below the MMP) – to assess the efficiency of immiscible displacement;

4) WAG injection of LPG and mixture 1 at a pressure of 30 MPa – to assess the effect of alternating water and gas injection on the oil recovery factor.

Results from visual micromodel studies of the WAG process confirm that alternating water and gas injection significantly improves sweep efficiency by blocking high-permeability channels with water and displacing residual oil from low-permeability zones with gas [20]. For each scenario, at least three replicate experiments on different core samples are planned. The displacement rate is 0.1–0.5 mL/min. The total injection volume is at least 2.0 pore volumes for continuous injection and at least 1.5 pore volumes of water + 1.5 pore volumes of gas for the WAG mode [5, 15].

Results and discussion

Results of PVT studies. The basic properties of the Mishrif formation reservoir oil, determined during the PVT studies, are presented in Table 1. The results confirm the oil characteristics used in the predictive model: reservoir oil density of 780 kg/m³, viscosity of 1.8 mPa×s at 95°C, saturation pressure of 15.2 MPa, gas content of 95 m³/m³, and formation volume factor of 1.42. The obtained values are in good agreement with data published for neighboring fields with similar geology (West Qurna-2, Rumaila) [1, 2].

The predicted results of swelling tests are presented in Table 2. It is expected that the addition of LPG will lead to the most significant oil swelling (swelling factor of 1.16) and the greatest viscosity reduction (down to 1.2 mPa×s), confirming the feasibility of using LPG as the primary gas agent for miscible displacement. The enriched mixture (60% C1 + 40% C3–C4) provides intermediate results (swelling factor of 1.09, viscosity of 1.4 mPa×s), while raw associated gas gives the minimum effect (swelling factor of 1.04). The increase in swelling factor when using LPG is associated with the high solubility of C3–C4 components in reservoir oil, leading to a reduction in interfacial tension and improved oil mobility [1, 3, 13].

Predicted minimum miscibility pressure values. The MMP values for various gas agents, predicted on the basis of previous numerical simulation and correlations reported in the specialized literature, are presented in Table 3. According to the predictions, miscible displacement at the reservoir pressure of 25 MPa can be achieved using the enriched mixture of 60% C1 + 40% C3–C4 with an MMP of 21.5 MPa, as well as using LPG

Table 1. Properties of reservoir oil, Mishrif formation, Nasiriyah field
Таблица 1. Свойства пластовой нефти формации Мишриф, месторождение Насирия

Parameter	Value
Reservoir oil density, kg/m³	780
Reservoir oil viscosity, mPa×s (95°C)	1.8
Saturation pressure, MPa	15.2
Reservoir temperature, °C	95
Gas content, m³/m³	95
Formation volume factor	1.42
Density of degassed oil, kg/m³	850

C3–C4 with an MMP of 18 MPa. Raw associated gas (MMP 32 MPa) and dry methane (MMP 38 MPa) do not provide miscible displacement at the existing reservoir pressure. Research on the potential for MMP reduction demonstrates that the introduction of chemical agents, such as surfactants, alcohols, and fatty acids, into the injected gas can significantly reduce the MMP and thereby expand the applicability range of the miscible displacement process [21]. At the same time, various correlation approaches often show a substantial scatter in MMP determination, highlighting the critical importance of its experimental validation [3, 6, 8, 22].

Within the planned slim-tube experimental program, it is intended to establish experimental MMP values for four types of gas agents: raw associated gas, enriched mixture consisting of 60% C1 and 40% C3–C4, LPG fraction C3–C4, and dry gas C1. For each of these agents, six to eight tests with pressure variation are planned. Accordingly, the total number of experiments will reach 24 to 32, which, with a duration of 8–12 hours per test, estimates the total timeframe of this program at 4–6 weeks. To confirm the adequacy of the developed predictive model, it is critical that the discrepancy between experimentally determined and predicted MMP values does not exceed 10% [6, 7, 14].

Predicted displacement efficiencies. Predicted displacement efficiencies for various core flooding scenarios are presented in Table 4. It is expected that the highest displacement efficiency (88–90%) will be achieved using LPG in the WAG mode at a pressure of 30 MPa. Continuous injection of the enriched mixture at pressures above the MMP provides a displacement efficiency of 80–84%, which significantly exceeds the performance of immiscible gas injection with raw gas (50–62%) at pressures below the MMP. The results will allow verification of the predicted oil recovery factors obtained from numerical simulation, evaluation of the effect of carbonate reservoir micro-heteroge-

Table 2. Predicted results of swelling tests (pressure 25 MPa)
Таблица 2. Прогнозные результаты испытаний на набухание (давление 25 МПа)

Parameter	Raw gas	Mixture 1	Liquefied petroleum gas C3–C4
Saturation pressure, MPa	16.8	14	12.5
Formation volume factor	1.48	1.55	1.65
Viscosity, mPa×s	1.6	1.4	1.2
Swelling factor	1.04	1.09	1.16

Table 3. Predicted minimum miscibility pressures (temperature 95°C)
Таблица 3. Прогнозные минимальные давления смешиваемости (температура 95 °C)

Gas agent	Minimum miscibility pressure, MPa	Reservoir pressure 25 MPa	Displacement type
Raw gas (associated)	32.0	*P* < MMP	Immiscible
Mixture 1 : 60% C1 + 40% C3–C4	21.5	*P* > MMP	Miscible
Liquefied petroleum gas C3–C4	18.0	*P* > MMP	Miscible
Dry gas C1	38.0	*P* < MMP	Immiscible

Note. Here and in Table 4, MMP stands for minimum miscibility pressure.

neity on displacement efficiency, and acquisition of experimental data for adjustment of relative permeability curves in the reservoir simulation model [5, 10, 15].

A key limitation of the completed experimental program is the quality and availability of core material. The carbonate rocks of the Mishrif formation are characterized by pronounced fracturing and brittleness. This circumstance significantly complicates both the extraction of intact core plugs and their subsequent transportation while preserving the original structural integrity. Furthermore, during the sample preparation stage, there is a possibility of altering the natural wettability of the pore surface, which could potentially have a substantial impact on the reliability of core flooding results. To minimize this risk, it is advisable to apply specialized core preservation techniques using reservoir or non-aqueous fluids. It is also critically important to minimize the time interval between core retrieval and the start of experimental studies [2, 15].

The second significant risk is associated with asphaltene precipitation, which may occur upon contact of reservoir oil with gas agents. This effect is particularly pronounced at high injection pressures. Potential asphaltene precipitation can cause plugging of the pore space of the core material, which in turn will distort the results of core flooding studies. For monitoring this phenomenon, it is recommended to:

– visually inspect the effluent fluids from the core outlet;

– measure the differential pressure during the experiment (a sharp increase may indicate plugging);

– analyse the produced oil for asphaltene content (SARA method: saturates, aromatics, resins, asphaltenes).

In the event of significant asphaltene precipitation, adjustment of the research program may be required, including tests with the addition of asphaltene inhibitors [10].

Scaling laboratory experimental results to reservoir conditions presents a separate methodological challenge. Laboratory core flooding experiments are conducted on samples 60–80 mm in length, whereas the distance between injection and production wells is hundreds of metres. The effect of macroscopic heterogeneity, including fractures and bedding texture, cannot be fully reproduced under laboratory conditions. To account for the scale effect, it is planned to perform parallel numerical simulation at the core scale and compare the results with experimental data [5, 9].

Financial and time risks are associated with a possible extension of the research duration should additional experiments become necessary. The baseline program is designed for 6–8 months; however, if unforeseen effects are identified (e.g., significant asphaltene precipitation or discrepancies with predicted values), the implementation period may be extended to 10–12 months. To manage this risk, intermediate control points are foreseen at which decisions on program adjustments will be made [14, 16].

Conclusion

This article presents a comprehensive program of key laboratory studies required for experimental verification of the predictive EOR model at the Nasiriyah field (Iraq, Mishrif formation). The program includes three interrelated blocks: PVT studies of reservoir oil, MMP determination by the slim-tube method, and core flooding experiments on core samples. Implementation of this program will allow verification of the results of previously performed numerical simulation and facilitate the transition from predictive calculations to a technologically sound industrial implementation

Table 4. Predicted displacement efficiency for core flooding experiments
Таблица 4. Прогнозные коэффициенты вытеснения для фильтрационных экспериментов

Gas agent	Condition	Continuous gas injection, %	Water-alternating gas, %
Liquefied petroleum gas C3–C4	*P* > MMP (30 MPa)	88	90
Mixture 1	*P* > MMP (30 MPa)	80	84
Raw gas	*P* < MMP (20 MPa)	50–62	–

project for gas EOR technology at the Nasiriyah field [1, 3, 16].

Predictive estimates indicate that injection of fractionated natural gas enriched with C3–C4 components can achieve miscible displacement at the existing reservoir pressure of 25 MPa. The expected displacement efficiency when using LPG is 88–90% in the WAG mode and 80–84% during continuous injection of the enriched mixture, which significantly exceeds the performance of the baseline waterflooding scenario and immiscible gas injection (50–62%). To confirm these predictions, a full scope of laboratory studies in accordance with international SPE standards is required [5–7, 15].

Prospects for further research include:

1) Conducting pilot testing in one of the sectors of the Nasiriyah field to verify the laboratory results under actual reservoir conditions;

2) Investigating the compatibility of gas agents with the Mishrif formation reservoir water, including assessment of the risk of mineral scale precipitation;

3) Optimizing the WAG injection mode (slug ratio, slug size, cycle duration) based on core flooding experimental results and numerical simulation;

4) Preparing a feasibility study for industrial technology implementation, taking into account the cost of gas agents, injection infrastructure, and expected incremental oil production [5, 16, 22].

The practical significance of this work lies in the fact that the proposed research program can be adapted for other Cretaceous carbonate reservoirs in Southern Iraq (West Qurna-2, Rumaila, Majnoon fields, etc.) that share similar geological and physical conditions. This opens up prospects for large-scale application of gas EOR technologies in one of the world's largest petroleum basins, which is of strategic importance for enhancing oil recovery and the sustainable development of Iraq's oil industry [2, 3, 16].

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