Application of Fractionated Gas for Enhanced Oil Recovery in Carbonate Reservoirs: A Case Study of Nasiriyah Oil Field, Iraq

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Abstract:
This study presents a comparative analysis of gas-based enhanced oil recovery (EOR) methods using fractionated associated gas in Middle Eastern carbonate reservoirs. The Nasiriyah oil field in Iraq, characterized by high-viscosity oil (15-25 cP) and heterogeneous carbonate formations, serves as the primary case study. Unlike Saudi Arabia and UAE strategies focusing on CO2-EOR, this research proposes using fractionated hydrocarbon gas enriched with C2-C6 components to reduce minimum miscibility pressure (MMP). An adaptive water-alternating-gas (WAG) process with variable gas composition was developed and evaluated through PVT modeling and hydrodynamic simulation. Results demonstrate that enriching associated petroleum gas with intermediate hydrocarbons can reduce MMP by 20-40%, enabling miscible displacement at achievable reservoir pressures. The proposed technology offers potential recovery factor improvement of 7-15 percentage points while utilizing local gas resources and reducing environmental impact from gas flaring.
Keywords*: Enhanced oil recovery; Fractionated gas; Carbonate reservoirs; Minimum miscibility pressure; Water-alternating-gas; Nasiriyah oilfield*

I.   Introduction

The Nasiriyah oil field, located in southern Iraq, represents one of the country's largest hydrocarbon accumulations with initial recoverable reserves estimated at approximately 14 billion barrels. The main productive horizons comprise Cretaceous deposits, specifically the Mishrif and Yamama formations, characterized by complex carbonate architectures with significant variability in reservoir properties [1, 2]. The Mishrif Formation exhibits a heterogeneous structure with alternating high and low-permeability zones, which directly impacts fluid flow behavior and requires careful zonal control during enhanced oil recovery operations [3].

The principal challenge at Nasiriyah stems from the properties of reservoir oil. Oil from the Mishrif and Yamama formations demonstrates relatively high viscosity under reservoir conditions, ranging from 15-25 cP and 10-18 cP respectively. These values significantly exceed those of oils from comparable regional fields. Oil density varies from 0.88-0.90 g/cm³ for Mishrif and 0.86-0.88 g/cm³ for Yamama, with sulfur content reaching 2.0-2.5% by weight. High oil viscosity correlates with elevated minimum miscibility pressures (MMP) for standard gases, rendering conventional gas-based EOR methods ineffective at existing reservoir pressures [4, 5].

Standard gas EOR methods, including dry methane or CO2 injection, face multiple limitations at Nasiriyah. The miscibility pressure for high-viscosity oils may be unattainably high or economically prohibitive to maintain. Furthermore, the large viscosity contrast between injected gas and reservoir oil leads to viscous instability, formation of gas "breakthrough tongues," and premature arrival at production wells. Reservoir heterogeneity, including fractures, caverns, and low-permeability interlayers, exacerbates these problems [6, 7].

This study aims to develop and evaluate an adaptive EOR technology using fractionated associated petroleum gas specifically designed for high-viscosity oil in heterogeneous carbonate reservoirs. The concept involves purposefully modifying gas composition by isolating or adding specific components to optimize displacement efficiency, particularly through reduction of MMP to achievable values [8, 9].

II.   Materials and Methods

2.1. Reservoir Characterization

The study focuses on the Nasiriyah oil field, with comparative analysis extending to major carbonate reservoirs in Saudi Arabia (Ghawar field, Arab-D formation) and the United Arab Emirates. Table 1 summarizes key reservoir and fluid properties across these fields. The geological structure of Nasiriyah comprises an anticlinal

fold trending northwest, with reef structures and faults significantly affecting reservoir productivity and requiring consideration during EOR planning [10].

Table 1. Comparative reservoir characteristics of Middle Eastern carbonate fields

Parameter	Nasiriyah (Iraq)	Ghawar (Saudi Arabia)	UAE (Typical)
Reservoir Age	Cretaceous	Jurassic	Jurassic-Cretaceous
Oil Viscosity (cP)	15-25	0.5-2.0	1.0-3.0
Oil Density (g/cm³)	0.88-0.90	0.80-0.85	0.82-0.87
Sulfur Content (wt%)	2.0-2.5	1.0-1.8	1.2-2.0
Reservoir Temperature (°C)	~76	Higher depth-dependent	Field-dependent
Potential EOR Recovery (%)	7-15	8-15	6-12

2.2. Gas Composition and Fractionation Process

Associated petroleum gas (APG) serves as the primary feedstock for fractionated gas production. Currently, significant APG volumes in Iraq are flared, causing environmental damage and representing economic loss. The fractionation process, based on differences in hydrocarbon boiling points, includes demethanizer, deethanizer, and propane-butane columns. This enables separation of fractions with specified compositions, particularly propane-butane-rich mixtures for MMP reduction [11].

Four primary gas composition options were evaluated:
• Option 0 (Base): Dry gas (predominantly CH_4) from APG
• Option 1: Dry gas enriched with propane (C_3H_8) at 10%, 20%, or 30 mol%
• Option 2: Dry gas enriched with CO_2 at 10-20 mol%
• Option 3: Combined mixtures ($CH_4 + C_3H_8 + CO_2$)

2.3. PVT and Hydrodynamic Modeling

PVT modeling was conducted using specialized software (PVTsim, CMG WinProp) with detailed reservoir fluid models. Minimum miscibility pressure was calculated for various gas mixtures through slim-tube simulation methodology. Sector hydrodynamic models were developed using Eclipse and CMG platforms for a representative area of the Nasiriyah reservoir (Mishrif/Yamama formations). The model incorporated dual-porosity representation of fractures and low-permeability matrix, with mineralogical composition specified for geochemical assessment [12, 13].

2.4. Adaptive WAG Process Design

The proposed technology involves adaptive water-alternating-gas injection with variable gas composition during different stimulation stages:

• Stage 1 (Cycles 1-N): Injection of "Rich Mixture 1" containing 25-30% C2-C5 components to create a miscible rim and minimize residual oil saturation near the injection well
• Stage 2 (Cycles N+1-M): Injection of "Lean Gas 2" (dry APG) to maintain reservoir pressure and displace oil already contacted by rich gas

The water-to-gas ratio and slug sizes were optimized through scenario calculations comparing standard WAG with the proposed adaptive approach.

III.   Results

3.1. Effect of Gas Composition on MMP

Figure 1 presents the relationship between gas composition and minimum miscibility pressure for Nasiriyah reservoir oil. The results demonstrate that enriching dry gas with intermediate hydrocarbons significantly reduces MMP. Specifically, addition of 25-30% propane-butane fraction reduces MMP by approximately 25-35% compared to dry methane, bringing miscibility within achievable reservoir pressure ranges (approximately 25 MPa for Mishrif formation).

Table 2 presents MMP values calculated for different gas compositions under reservoir conditions of 76°C and 25 MPa pressure. The results confirm that enriched gas mixtures achieve miscible displacement at pressures that may be insufficient for dry gas or even CO_2 alone.

Table 2. Minimum miscibility pressure for various gas compositions

Gas Composition	MMP (MPa)	Reduction vs Dry Gas (%)
Dry gas (CH4)	32.5	—
CH4 + 10% C3H8	28.2	13.2
CH4 + 20% C3H8	24.8	23.7
CH4 + 30% C3H8	21.5	33.8

3.2. Hydrodynamic Simulation Results

Comparative hydrodynamic simulations were conducted for two scenarios: Scenario A (standard WAG with dry gas) and Scenario B (adaptive WAG with fractionated gas). The simulations were run over a 20-year period for a representative sector model. Results demonstrate significant advantages for the adaptive approach:

Table 3. Comparative simulation results (20-year forecast)

Parameter	Scenario A (Standard WAG)	Scenario B (Adaptive WAG)
Cumulative Oil Production (MMbbl)	12.5	15.2
Recovery Factor Increase (%)	6.8	10.4
Peak GOR (scf/stb)	2,850	1,920
Gas Breakthrough Time (years)	3.2	5.8

The adaptive WAG scenario demonstrates 21.6% higher cumulative oil production and delays gas breakthrough by approximately 2.6 years. The improved displacement efficiency results from better mobility ratio control and miscible displacement in the near-wellbore region during initial cycles.

3.3. Economic Assessment

Economic evaluation was conducted considering CAPEX for modular fractionation units, injection system modifications, and OPEX for gas processing. Revenue estimates were based on incremental oil production at $75/bbl oil price. Key economic indicators:
• Net Present Value (NPV): $185 million
• Internal Rate of Return (IRR): 22.5%
• Payback Period: 3.8 years

Sensitivity analysis indicates economic viability across oil price range of $55-95/bbl, with NPV positive at prices above $48/bbl.

IV.   Discussion

The results confirm that fractionated gas technology addresses the key challenges of high-viscosity oil displacement in heterogeneous carbonate reservoirs. By reducing MMP through enrichment with intermediate hydrocarbons, miscible displacement becomes achievable at realistic reservoir pressures. The adaptive WAG approach provides additional benefits through staged composition management, optimizing both displacement efficiency and economics.

Compared to Saudi Arabia and UAE strategies focusing on CO2-EOR, the proposed approach offers several advantages for Nasiriyah conditions: (1) utilization of local APG resources, reducing dependence on external CO2 sources; (2) reduced environmental impact from gas flaring; (3) potentially lower implementation costs due to existing gas infrastructure at the field [14, 15].

However, successful implementation requires addressing several factors: detailed laboratory confirmation of MMP values through slim-tube experiments; reservoir characterization to identify optimal injection patterns; and operational protocols for managing variable gas composition during injection cycles. The integration of CO2 from industrial sources could further enhance displacement efficiency while providing environmental benefits through carbon sequestration [16].

V.   Conclusion

This study demonstrates the potential of fractionated gas-based EOR technology for enhancing oil recovery from the Nasiriyah carbonate reservoir. The key conclusions are:

1. High oil viscosity (15-25 cP) at Nasiriyah results in elevated MMP for standard gases, rendering conventional gas EOR methods ineffective at existing reservoir pressures.
2. Enriching associated gas with C2-C6 components can reduce MMP by 25-35%, enabling miscible displacement at achievable pressures.
3. The proposed adaptive WAG technology with variable gas composition shows superior performance compared to standard WAG, with 21.6% higher cumulative production and delayed gas breakthrough.
4. Economic analysis confirms project viability with NPV of $185 million and IRR of 22.5% at $75/bbl oil price.
5. The technology provides environmental benefits through APG utilization, reducing gas flaring and associated emissions.

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