[Technical Report]

Performance of Iranian Naturally Fractured Cores under Miscible Displacement Experiments

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Determining the feasibility of miscible displacement process to increase oil recovery from Iranian naturally fractured reservoirs is the subject of this study. For that purpose, miscible displacement experiments including liquefied petroleum gas (LPG) injection were carried out under reservoir conditions on composite cores, consisting of reservoir fractured core plugs of the chosen rock type. Results of experimental studies indicated that LPG miscible flooding could maximize oil recovery. In this paper, results of the Iranian fractured core flooding experiments are presented.

Keywords
Naturally fractured reservoir, EOR process, Miscible displacement, Composite core

1. Introduction

Limestone and dolomite reservoirs constitute one of the largest sources of crude oil supply in the world. Approximately 65% of present world production comes from carbonate reservoirs mostly located in the Middle East, Mexico, and Canada. Although fractured reservoirs are scattered throughout the world, one of the highest concentration of reserves of this type is in the southwest of Iran and northeast of Iraq. The oil-in-place in the Middle East fractured reservoirs represents 25-30% of the total oil in place in that area. This percentage may also be representative on worldwide scale[1)].

Efforts to recover more oil from an Iranian naturally fractured reservoir led to the initiation of this laboratory study. Given the characteristics of this reservoir (depth more than 3000 m, 30 API, carbonate rock, temperature 113°C, pressure 307 bar), the enhanced oil recovery experiments have to be conducted under very demanding conditions. Due to the fractured type of the reservoir rock, attention has centered on the liquefied petroleum gas (LPG) displacement.

Adequate prediction of the displacement efficiency of miscible displacement is fundamental to the design of the miscible flood. Some of the important input variables for a successful design are pore volumes of displacing fluid injected, type of displacing fluid, mobilities of the displacing fluid and reservoir fluids, and reservoir heterogeneity[2)]. The effects of these variables on the displacement efficiency are best determined from laboratory displacement experiments.

The purpose of this paper is to examine the feasibility of applying miscible gas flooding scheme for a naturally fractured reservoir in an oil field in Iran.

2. Core Preparation and Properties

The cores used in the displacement experiments were obtained in preserved conditions from an Iranian naturally fractured reservoir. Properties of the four cores, labeled A1, B1, C1, and D1 are shown in **Table 1**. For determination of minimum miscibility pressure (MMP), we used synthetic core. This synthetic core is labeled S1 in **Table 1**.

3. Fluid Properties

Compositions of the displacing and displaced fluids are presented in **Table 2**. The physical properties of the displacing and displaced fluids are listed in **Table 3**. The dead oil was used as displaced fluid and LPG was used as displacing fluid in experiments. Two types of displacement experiments were conducted in the laboratory:
1) Fluid injection in synthetic core for determination of MMP.

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Table 1 Physical Properties of Cores

Core No.	Lithology	Depth [m]	Porosity [%]	Permeability [md]	Grain density [g/cm^3]
A1	Dolomite and limestone	3550.9-3551.13	17.3	198	2.771
B1	Dolomite and limestone	3553.90-3556	15.4	91.7	2.758
C1	Limestone	3509.30-3509.50	11.2	18	2.836
D1	Limestone	3714.10-3714.38	11.5	19.5	2.827
S1	Sandstine	—	35	5000	—

Table 2 Compositions of Displacing and Displaced Fluids

Component	Dead oil	LPG
Carbon dioxide	0.74	0
Hydrogen sulfide	1.3	0
Methane	0.59	0
Ethane	1.2	0
Propane	4.21	30
Butane	5.13	70
Isopentane	2	0
Pentane	4	0
Hexanes	6	0
Heptan and heavier	74.83	0

Table 3 Physical Properties of Displacing and Displaced Fluids

Oil density at 132 bar and 113°C	[kg/m^3]	819
Oil viscosity at 132 bar and 113°C	[Pa·s]	2.92E-03
LPG density at 132 bar and 113°C	[kg/m^3]	522
LPG viscosity at 132 bar and 113°C	[Pa·s]	1.42E-04

2) Fluid injection in composite core (made from naturally fractured cores) to evaluate the effectiveness of miscible LPG injection.

4. Experiments

Figure 1 is a schematic diagram of the displacement apparatus for MMP determination and core flooding experiments. Four Rossi Motoriduttori positive displacement synthetic oil pumps were used for fluid injection. Various fluids (brine, crude oil, and LPG) contained in the three 1.5 *l* cylinders were displaced by synthetic oil. The core holder and three cylinders were placed in a constant temperature air bath oven. The overburden pressure was applied using a hydraulic hand pump containing synthetic oil. During the experiments, inlet and outlet pressures of core were measured by electronic pressure gages and the pressure drop across the core was recorded continuously using the differential pressure transducer. A differential valve as a backpressure regulator maintained the flooding pressure. The effluent was flashed into a 0.2 *l* oil and gas separator at atmospheric pressure. The liquid hydrocarbon was collected by a collecting pump and the volume was measured, while the effluent gas was continuously measured using a wet type gas flow meter.

The dead crude oil was used as reservoir fluid in all of the experiments and the temperature of the oven kept at 113°C simulating the reservoir temperature.

5. MMP Determination Experiments

In the MMP determination experiments, the LPG was injected at a rate of 3.33×10^{-9} m^3/s at different pressures. For each experiment, the synthetic core was saturated with crude oil at reservoir temperature, and the oil was displaced with the LPG at constant pressure. Cumulative oil recovery was measured by oil collecting pump as a function of LPG volume injected. The experiment was then repeated at different pressures.

In these experiments, the recovery is expected to increase by increasing displacement pressure. The point at which the curve breaks over, or at which extrapolations of the two parts of the curve intersect, is termed MMP for a recovery *versus* pressure plot[3]. Additional recovery above MMP is generally minimal. **Figure 2** shows oil recovery at different displacement pressures. As we can see the MMP is about 132 bar. At this pressure the breakthrough oil recovery was about 94% of original oil in place (OOIP). This breakthrough recovery represents the maximum recovery possible with LPG flood.

6. Core Flooding Experiments

Preserved cores from the actual fractured reservoir were used in the core flooding experiments. The selection of reservoir cores for these tests was based on rock characteristic and a detailed study of geology of the entire reservoir. The cores were sampled from the pay zone of interest and chosen to properly represent the main rock types occurring in the reservoir formation.

Preserved core plugs of 0.075 m in length and 0.0254 m in diameter were used to make a composite core. Placing the ends of the single plugs in direct contact made the composite core. Before preparing a composite core, the brine permeability was measured

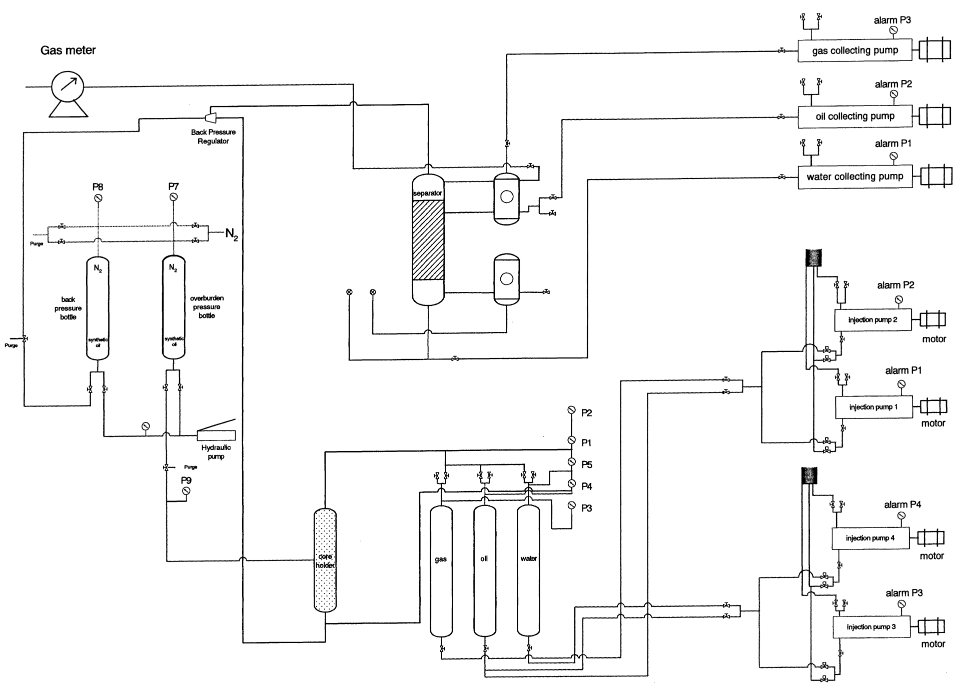

Fig. 1 Core Flooding Apparatus

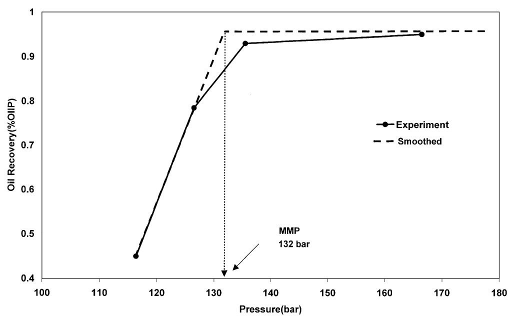

Fig. 2 Experimental Results for MMP Determination

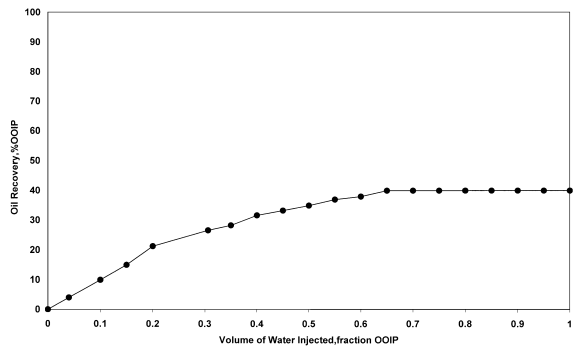

Fig. 3 Performance of Waterflood on Naturally Fractured Composite Core

for each plug. These data were required to determine optimum core ordering in making the composite core. The plugs were assembled using Huppler technique[4].

In waterflooding tests, a ten percent NaCl solution was used as the displacing fluid. To avoid the influence of the capillary forces on waterflood relative permeability measurements, the scaling criterion described by Kyte and Rapoport[5] was applied. Accordingly, an injection rate of 5.3×10^{-8} m^3/s was used. Since the capillary forces for miscible displacement are negligible, the scaling criterion was not applied for LPG flood tests and a rate of 1×10^{-9} m^3/s was used for LPG injection. By using Slobod and Howlett[6] expression for the critical rate, this rate of LPG injection was below the critical rate.

7. Results of Flooding Experiments

Figure 3 shows the results of waterflood tests. Waterflood on the composite core recovered 22% OOIP at breakthrough and about 40% OOIP at 96% watercut.

The LPG flood performance on a naturally fractured composite core is shown in **Fig. 4**. As we can see, the LPG breakthrough recovery was about 70% OOIP, much lower than the oil recovery from synthetic core in MMP experiment. The main causes for a larger miscible flood residual oil saturation in core flood are: (1) by-passing of oil located in low permeability matrix occlusions that are not contacted by LPG, (2) channeling of the LPG in high permeability fractures, and (3) gravity segregation. Incremental recovery at breakthrough was about 48% OOIP more than would have

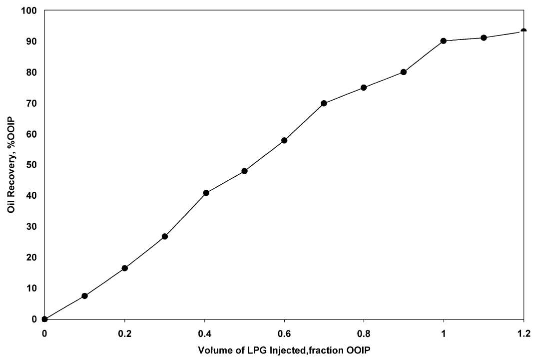

Fig. 4 Performance of LPG Flood on Naturally Fractured Composite Core

been realized under waterflood. Also, oil recovery increased to 90% OOIP at about 1.2 OOIP LPG injection which is over twice the waterflood ultimate oil recovery. This is one of the important characteristics of the miscible flood in naturally fractured cores. A considerable amount of oil is recovered after breakthrough.

8. Conclusions

On the basis of the miscible flood experiments the following conclusions are derived:
(1) The results of MMP experiments indicated that LPG displacements were dominantly miscible processes under the reservoir conditions. Runs using the synthetic core resulted in a breakthrough oil recovery of approximately 94% OOIP. This breakthrough recovery represents the maximum recovery possible with LPG flood.
(2) Waterflood test on the naturally fractured composite core indicated that breakthrough recovery was 22% OOIP, while ultimate recovery was 40% OOIP at 96% watercut.
(3) Ultimate recovery by miscible displacement was almost twice as much as waterflood recovery. This means that the incremental recoveries were as much as waterflood recoveries.

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References

1) Saidi, A. M., “Reservoir Engineering of Fractured Reservoirs,” Total Edition Press, Paris (1987).
2) Stalkup, F., “Miscible Displacement,” SPE Monograph Series, (1983).
3) Danesh, A., “PVT and Phase Behavior of Petroleum Reservoir Fluids,” Elsevier Science, Netherlands (1998).
4) Huppler, J. D., *JPT*, 539 (1969).
5) Kyte, J. R., Rapoport, L. A., *Trans. AIME*, **213**, 423 (1958).
6) Slobod, R. L., Howlett, W. E., *SPEJ*, March, 1 (1964).

要　　旨

イラン産天然フラクチャーコアを使ったミシブル置換効果の実験的検証

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イランにおける天然フラクチャー油層に対するミシブル攻法による油の回収量増加の可能性を実験により確認した。油層から得られた天然フラクチャーコアプラグを，油層を代表する岩質に合致するように組み合わせたコンポジットコアを使用し，油層条件下で，LPG によるミシブル置換実験を行った。

同様の条件での水圧入の場合と比較すると，ミシブル置換ではブレークスルー時で 3 倍以上，最終的にも 2 倍以上の油が回収された。またミシブル置換においては，ブレークスルー後，さらに OOIP（原始埋蔵量）の 20% の追加回収が得られ，天然フラクチャー型油層の特徴的な回収挙動が確認された。ミシブル置換による最終的な回収率は 90% と，均一なコアで得られる回収率とほぼ同様な値となり，LPG を使ったミシブル攻法は油回収に最大の効果があることが確認された。