# Enhanced oil recovery techniques and $CO_2$ flooding

*M. Al-Jarba and B. D. Al-Anazi*

PROFESSIONAL PAPER

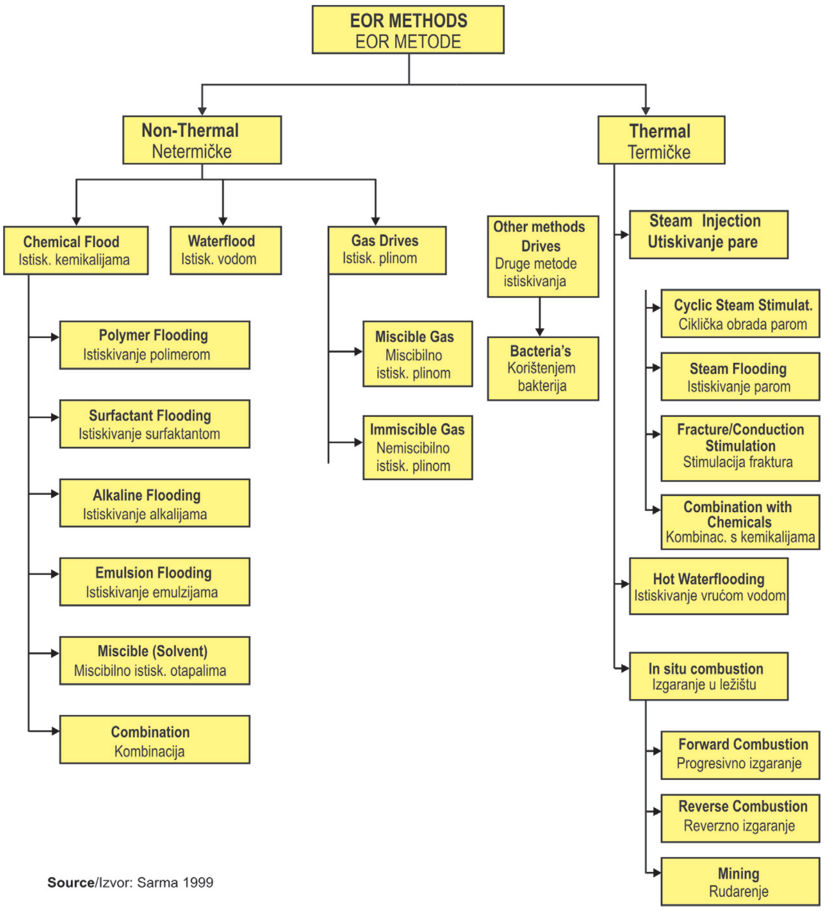
**Over the years, interest in enhanced oil recovery (EOR) has been tempered by the increase in oil reserves and production. Many techniques have been investigated in the laboratory and the field for improving oil recovery. The discovery of major oil fields in the world added large volumes of oil to the worldwide market. In addition, estimates of reserves from reservoirs in the Middle East increased significantly, leading to the expectation that the oil supply will be plentiful. Although large volumes of oil remain in mature reservoirs, the oil will not be produced in large quantities by EOR processes unless these processes can compete economically with the cost of oil production from conventional sources. Thus, as reservoirs age, a dichotomy exists between the desire to preserve wells for potential EOR processes and the lack of economic incentive because of the existence of large reserves of oil in the world.**

*Key words:* recovery, enhanced oil recovery methods, oil and $CO_2$ miscibility

## 1. Introduction

Crude oil development and production from oil reservoirs can include up to three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. During primary recovery, the oil is recovered by natural energy or gravity drive into the wellbore, combined with artificial lift techniques which bring the oil to the surface. On average, only about 10 percent of a reservoir's original oil in place is typically produced during primary recovery. Secondary recovery techniques to the field's productive life generally include injecting of water or gas to preserve the reservoir pressure and to displace oil. The result is increasing of the oil recovery from 20 to 40 percent of the original oil in place. However, with much of the easy-to-produce oil already recovered from oil fields, producers have attempted several tertiary, or enhanced oil recovery (EOR) techniques, that offer prospects for ultimately producing 30 to 60 percent, or more, of the reservoir's original oil in place. Three major categories of Enhanced Oil Recovery have been found to be commercially successful to varying degrees:

- Thermal recovery, which involves steam or heat injection, in general to lower the viscosity of heavy oil, and improve its ability to flow through the reservoir.
- Gas injection, which uses gases such as natural gas, nitrogen, or carbon dioxide, that release additional oil by lowering interfacial tension and viscosity.



**Source**/Izvor: Sarma 1999

**Fig. 1. Overview of EOR methods**[2]
Sl.1. Pregled EOR metoda[2]

Gas injection accounts for nearly 50 percent of EOR production.

- Chemical injection, which can involve the use of long-chained molecules called polymers to increase the effectiveness of waterfloods, or the use of detergent-like surfactants to help lower the surface tension that often prevents oil droplets from moving through a reservoir.[7]

## 2. $CO_2$ flooding

$CO_2$ flooding is an effective enhanced oil recovery process. It appeared in the 30's and had a great development in the 70's. Over the 30 years of production practice, CO2 flooding has become the leading enhanced oil recovery technique for light and medium oils. It can prolong the production lives of light or medium oil fields nearing depletion under waterflood by 15 to 20 years, and may recover 15% to 25% of the original oil in place.

The phase behavior of $CO_2$/crude-oil systems has been investigated extensively since the 60's. This attention was at its peak in the late 70's and early 80's, at the onset of many $CO_2$ miscible flooding projects and higher oil prices. Interest continues as new projects come on stream and earlier projects mature. Studies to understand the development, and predict the MMP for both pure and impure $CO_2$ injection have been ongoing for over thirty years.

Various attempts with the target of developing methods for measuring and calculating the MMP exist in the literature. Many of these are based on simplifications such as the ternary representation of the compositional space. This has later proven not to honor the existence of a combined mechanism controlling the development of miscibility in real reservoir fluids. Zick (1986) and subsequently Stalkup (1987) described the existence of a vaporizing/condensing mechanism. They showed that the development of miscibility (MMP) in multicomponent gas displacement processes could, independent of the mechanism controlling the development of miscibility, be predicted correctly by one dimensional (1D) compositional simulations. A semi-analytical method for predicting the MMP was later presented by Wang and Orr (1997) who played an important role in the development and application of the analytical theory of gas injection processes.[10]

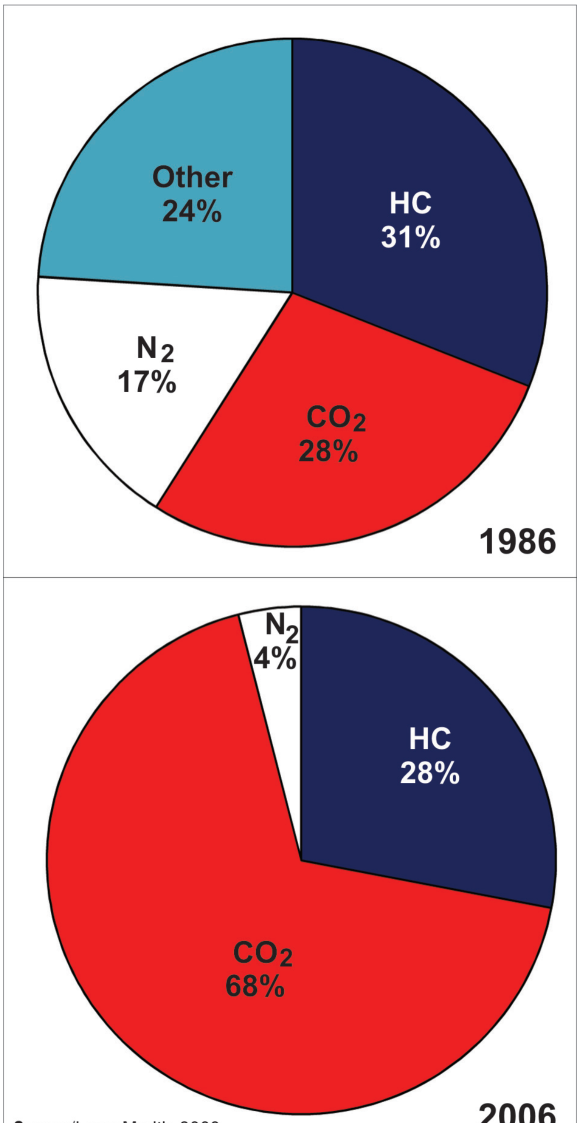
### 2.1. Carbon Dioxide as a displacement fluid

Carbon dioxide is one of the most considerably and useful compounds found on the Earth. In 1952 *Whorton et al.*, by using $CO_2$, received the first patent for oil recovery.

Advances in $CO_2$ flooding technology during the 60's and 70's added considerably to $CO_2$ displacement mechanisms. A 1982 survey revealed a 65% increase in the number of $CO_2$ projects over 1980.[9]

According to the latest (2008) EOR survey, published biannually in the Oil and Gas Journal, gas injection has become the largest EOR process in the U.S., displacing the long reigning thermal processes. Enhanced oil recovery (EOR) activities in the United States account for nearly 13% of the U.S. domestic production.

The change in the U.S. EOR application and distribution scenarios from 1986 to 2006 are shown in Figure 2.



**Source**/Izvor: Moritis 2006

**Fig. 2. The changing mix of gas injection EOR**
Sl. 2. Promjene vrste plina za utiskivanje u EOR procesima

It shows the dynamics of various gas injection EOR processes and current U.S. dominant EOR methods. This figure clearly indicates that, with the exception of $CO_2$ and HC processes, the share of all the other EOR processes has significantly decreased or been reduced to zero in the last two decades. The share of $CO_2$ and hydrocarbon gas processes has nearly doubled in two decades. Further scrutiny of the gas injection EOR performance shows that within the last twenty years the miscible $CO_2$ projects have increased from 28 in 1984 to 80 in 2006. Their production during the same time period has grown from 31 300 bbl/d (4 977 $m^3$/d) to 234 420 bbl/d (37 273 $m^3$/d) in 1984 to 124 500 bbl/d (19 796 $m^3$/d) in 2000 in spite of their decreasing numbers. However, this trend has been reversed since 2002, and the EOR production from hydrocarbon gas floods has currently decreased to 95 800 bbl/d (15 232 $m^3$/d).

## 2.2 Advantages and disadvantages of carbon dioxide injection

When oil and water contain a significant amount of dissolved carbon dioxide their viscosities, densities, and compressibilities are modified in a direction which helps oil displacement from the reservoir. Therefore, the use of carbon dioxide in oil recovery should be considered where carbon dioxide is available in sufficient quantities and is economically priced.[7]

Advantages, achieved with carbon dioxide flooding:

1. Miscibility can be attained at low pressures
2. Displacement efficiency is high in miscible cases
3. This process aids recovery by solution gas drive
4. It is useful over a wider range of crude oils than hydrocarbon injection methods
5. Miscibility can be regenerated, if lost.

The miscible carbon dioxide process is primarily used for medium and light crude oils. In the case of immiscible carbon dioxide displacement, advantage is taken of the swelling of crude oil and the reduction in crude oil viscosity upon carbonation. Because of high solubility of carbon dioxide in crude oil, for reservoirs containing highly under-saturated crude oils or heavy oils, the benefits of immiscible carbon dioxide flooding are also significant[13], as shown in Figure 3 for $CO_2$ miscible process

Disadvantages, which restrict this method, can be categorized as follows:

1. Availability of carbon dioxide resources
2. Transportation costs
3. Under certain conditions poor sweep and gravity segregation can be obtained
4. Corrosion of down-hole and surface equipments
5. Necessity for produced gas recycling.

## 2.3. Reservoir screening criteria for carbon dioxide injection

There are several publications for screening reservoirs with potential of $CO_2$ flooding. These screening guidelines are very broad and are intended only to help identify candidate reservoirs that might warrant more thorough evaluation to assess their $CO_2$ miscible flooding suitability. These guidelines are summarized in Table 1.[17]

For a reservoir to be a $CO_2$-miscible flooding candidate, miscibility pressure must be attainable over a significant volume of the reservoir. Miscibility pressure for $CO_2$ often is significantly lower than the pressure required for miscibility with natural gas, flue gas, or nitrogen. The high pressure required for dynamic miscibility limits opportunities for miscible flooding with these gases. However, this often is not the case with $CO_2$ and its miscibility can be attained at shallower depths for a much wider spectrum of oils.

Miscibility pressure usually increases with decreasing oil gravity. Reservoirs containing oils with gravities lower than about 22°API (921 kg/m$^3$) generally can't be $CO_2$-miscible flood candidates. Reservoirs shallower

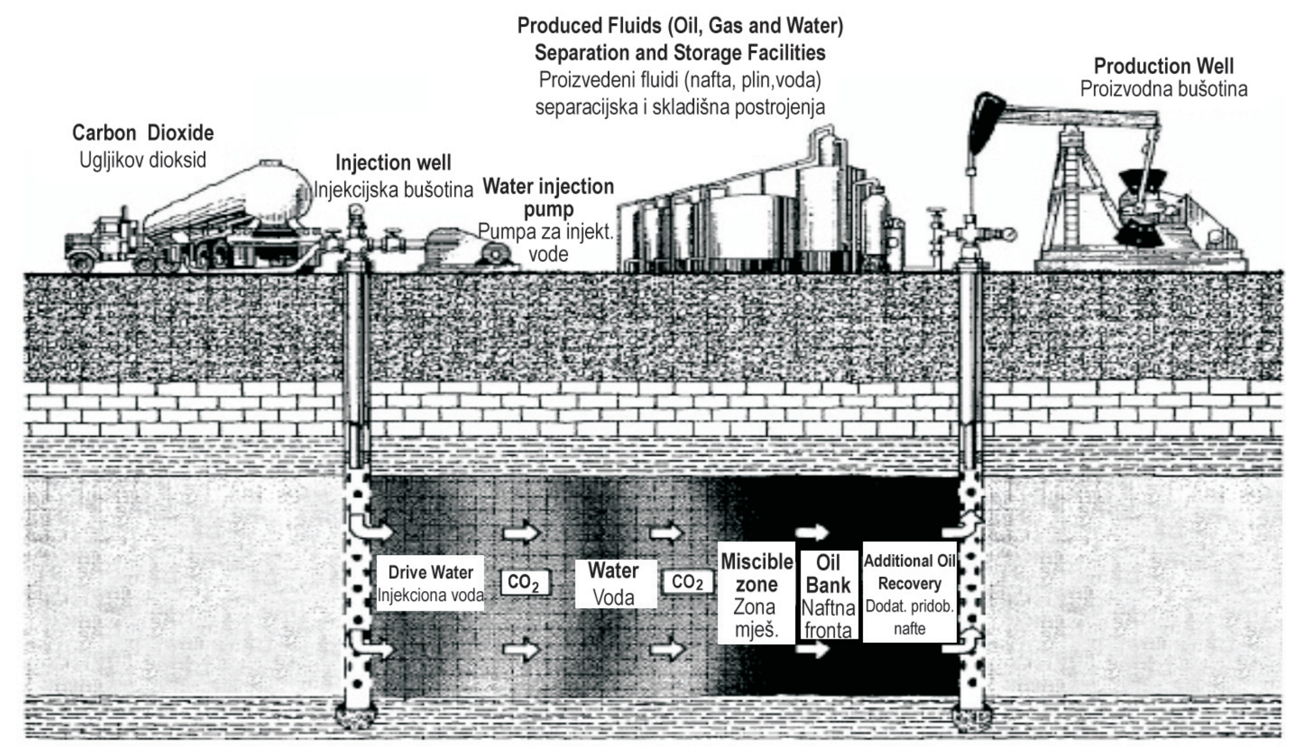


**Fig. 3. $CO_2$ miscible process (Source: Green and Willhite,1998)**
Sl. 3. $CO_2$ miscibilni procesi (Izvor: Green and Willhite,1998)

**Table 1. Depth vs. oil gravity screening criteria for $CO_2$ flooding**[13]

| For $CO_2$ miscible flooding | | | |
|---|---|---|---|
| Oil gravity °API | kg/m$^3$ | Depth must be greater than:<br>Feet | m |
| >40 | < 824 | 2 500 | 762 |
| 32-39.9 | 825-865 | 2 800 | 850 |
| 28-31.9 | 865-886 | 3 300 | 1 006 |
| 22-27.9 | 887-921 | 4 000 | 1 219 |
| <22 > | 921 | Fails miscible, screen for immiscible | |
| For imiscible $CO_2$ flooding | | | |
| 13-21.9 | 922-978 | 1 800 | 544 |
| <13 | > 978 | All oil reservoirs fail at any depth | |

Source: Jiahang, 2003

than about 2 500 ft (762 m) can't usually be a candidate because at this shallow depth even a relatively low miscibility pressure cannot be attained without fracturing the reservoir.

Reservoir heterogeneity is also another parameter, which determines the suitability of a reservoir for $CO_2$ flooding. Water-flood history, geology, logs, and well transient tests can be indications of reservoir heterogeneity.

Oil displacement strongly depends on factors, which are related to the phase behaviour of $CO_2$-crude oil mixtures. Reservoir's temperature and pressure and crude oil composition are the main agents in this respect. Dominated displacement characteristics for a given $CO_2$-displacement falls into one of the four regions as shown in the table 2.

Because of carbon dioxide's low viscosity, the viscosity ratio with reservoir oils will invariably be unfavorable. Therefore the mobility ratio of the displacement will be unfavorable unless the $CO_2$ relative permeability is sufficiently reduced by alternate water injection, semi-solid or heavy-liquid precipitation, or other factors to keep the mobility ratio favorable. Unfavorable mobility ratio adversely affects sweep-out and can hasten $CO_2$ slug destruction in the gas-driven slug process by viscous fingering. For these reasons, reservoirs containing oils of relatively high viscosity are not suitable candidates for $CO_2$ miscible flooding.

As in the case of hydrocarbon-miscible flooding, severe reservoir heterogeneity causing excessive production of $CO_2$ is to be avoided. Although some $CO_2$ production is to be expected even in the best-performing floods and although compression and re-injection of produced $CO_2$ may be economically sound in specific projects, severe channelling caused by extreme stratification or fracturing can reduce the ratio of oil recovered per gross cubic foot of $CO_2$ injected to an uneconomical value, and reservoirs with these characteristics should be avoided. As in the hydrocarbon-miscible processes, economic factors determine the minimum oil saturation, which is accepted for $CO_2$ flooding. However, as a rough guideline, oil saturation should not be less than about 20%.[16]

## 2.4. Future Development

Enhanced oil recovery from $CO_2$ flooding is expected to continue to increase in future years under most world oil price scenarios. As a part of the U.S. Department of Energy's Oil and Gas Supply Model, which forecasts future oil and gas production in the United States, Advanced Resources developed and enhanced oil recovery sub module that specifically assesses the economics of $CO_2$ – EOR projects in the United States. The field – based economic model evaluates the production costs of existing $CO_2$- EOR project in the U.S., as well as the development costs for expanding $CO_2$ flooding into new depleted oil fields, providing the ability to systematically forecast future EOR production. Alaskan $CO_2$ – EOR production, which is not simulated in this model, was assumed to remain constant at the current level of about 2 400 m$^3$ /day (15 000 bbl/d).

**Table 2. Dominant displacement characteristics for carbon dioxide displacement process**[14]

| Carbon dioxide injection process | Reservoir criteria | Oil recovery mechanisms |
|---|---|---|
| Low pressure applications | Pressures less than 1 000 psia (68.9 bar). Shallow and viscous oil fields where water or thermal methods are inefficient | Oil swelling and viscosity reduction |
| Intermediate pressure, high temperature applications | 1 000<$p$<2 000 to 3 000 psia<br>(68.9<$p$<137.9 to 206.8 bar) up to reservoir temperature | Oil swelling, viscosity reduction and crude vaporization |
| Intermediate pressure, low temperature <122 °F (50 °C) applications | 1 000<$p$<2 000 to 3 000 psia (68.9<$p$<137.9 to 206.8 bar). Temperature <122 °F (50 °C) | Oil swelling, viscosity reduction and blow down |
| High pressure<br>Miscible applications | Pressures greater than 2 000 to 3 000 psia<br>(137.9 to 206.8 bar) | Miscible displacement |

Source: Klins 1984

## References

1. Ahmed, T. A.: Generalized Methodology for Minimum Miscibility Pressure, SPE 39034, Sao Paulo, Brazil, 1997.
2. Alston, R.B., et all.: $CO_2$ Minimum Miscibility Pressure; A Correlation for Impure $CO_2$ Streams and Live Oil Systems; SPEJ, pp 268-274, April, 1985.
3. CHUNG, F.H. et all.: Recovery of viscous oil under high pressure by $CO_2$ displacement: A laboratory study; SPE paper 17588 presented at the SPE International Meeting on Petroleum Engineering, held in Tianjin, China, November 1 - 4, 1988.
4. Dake, L.P.: Fundamentals of Reservoirs Engineering, Elsevier Science B.V. 1978.
5. Emera, M.K., Sarma, H.K.: Genetic Algorithm (GA) - based Correlations offer More Reliable Prediction of (MMP), Canadian International Petroleum Conference, Calgary, Alberta, Canada, June 7 – 9, 2005.
6. Emera, M.K., Sarma, H.K. Genetic Algorithm (GA) - based Correlations offer More Reliable Prediction of $CO_2$ Oil Physical Properties, Canadian International Petroleum Conference, Calgary, Alberta, Canada, June 13 – 15, 2006.
7. Gozalpour, F. et all: CO2 EOR and Storage in Oil Reservoirs Oil & Gas Science and Technology; Rev. IFP, Vol. 60, No.3, pp. 537 546, 2005.
8. GRIGG, R.B.; Dynamic phase composition, density, and viscosity measurements during $CO_2$ displacement of reservoir oil; SPE paper 28974 presented at the SPE International Symposium on oil field chemistry held in San Antonio, TX, USA, Feb. 14-17, 1995.
9. HOLM, L.W. and JOSENDAL, V.A.: Mechanisms of oil displacement by carbon dioxide; JPT, 1427-1438, 1974.
10. Jessen. K, et all: Fluid Characterization for Miscible EOR projects and $CO_2$ sequestration. SPE paper 97192, SPE Annual Technical Conference and Exhibition, 9 – 12 October, Dallas, Texas, 2005.
11. KOKAL, S.L. and SAYEGH, S.G.: Phase behavior and physical properties of $CO_2$-saturated heavy oil and its constitutive fractions: Experimental data and correlations; Journal of Petroleum Science and Engineering, Vol. 9, 4, 289-302, 1993.
12. Kuo,S.S.: ARCO Resources Technology Predication of Miscibility for the Enriched Gas – paper SPE 14152 – September 22 - 25, 1985.
13. Lee, J.L.: Effectiveness of Carbon Dioxide Displacement under Miscible and Immiscible Conditions; Report RR-40, Petroleum Recovery Inst., Calgary, March 1979.
14. Puttagunta, V.R., et all: Correlation and prediction of heavy oil and bitumens containing dissolved gases, Part II: Saskatchewan heavy oils saturated with gas mixtures; AOSTRA Journal of research, Vol. 7, 251-258, 1991.
15. SRIVASTAVA, et all: Measurement and prediction of PVT properties of heavy and medium oils with carbon dioxide - paper presented at the 6th UNITAR International conference on heavy crude and tar sands, Houston, Feb. 12-17, 1995.
16. Stalkup Jr., F.I.: Miscible Displacement; SPE Monograph Series, 139, 1984.
17. Taber, J.H., et all: EOR Screening Criteria Revised – Part 1 : Introduction to Screening Criteria and Enhanced Recovery Field Projects. SPE Reservoir Engineering, 12, 3, 189-198, 1997.

❖

Authors:

**Mojsin Al-Jarba**, Drilling Supervisor Assistant LUKOIL Saudi Arabia Energy
E-mail: mjrbaa@luksar.com.sa

**Bandar Duraya Al-Anazi**, Research Assistant, King Abdulaziz City for Science & Technology
E-mail: bandar.alanazi@gmail.com