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ORIGINAL PAPER - PRODUCTION ENGINEERING

A new approach for predicting oil recovery factor during immiscible CO_2 flooding in sandstones using dimensionless numbers

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Abstract

CO_2 injection is one of the most promising techniques to enhance oil recovery. The most favorable properties of CO_2 made this method popular and it has been widely used since 1950. Experimentally, the effect of CO_2 injection on incremental oil recovery is widely measured by the core-flooding approach. An accurate estimation of the recovery factor is required to analyze the performance of the method to design the enhanced oil recovery method successfully. Hence, knowledge of the effects of different parameters on recovery is essential. Various reported experimental CO_2 core-flooding data for the immiscible condition in sandstones were analyzed to develop the parametric relationships affecting ultimate oil recovery using data analytics. Selected data support a wide range of porosity (10.8–37.2%), permeability (1–18000 mD), injection pressure (2.73–11.44 MPa), injection rate (0.1–1.0 cm^3/min), and crude oil types, which enhance the methodology used to develop more comprehensive dimensionless numbers and correlations to predict the oil recovery. Series of new dimensionless numbers were defined and used for the study to develop a correlation for predicting oil recovery factor. Capillary number, relative radius, injection pressure ratio, and oil composition number are used as dimensionless numbers in our approach. The oil recovery prediction by the developed correlation was in agreement with the experimental data. The proposed correlation shows that capillary number is the most effective parameter when predicting oil recovery.

Keywords Gas flooding · Dimensionless numbers · Capillary number · Oil recovery · Immiscible gas injection

List of symbols

N_c	Capillary number (dimensionless)
R_r	Relative radius (dimensionless)
MMP	Minimum miscibility pressure (MPa)
MCM	Multi-contact miscibility
OCN	Oil composition number (dimensionless)
PRF	Predicted oil recovery factor (dimensionless)
P_i	Injection pressure (MPa)
P_r	Injection pressure ratio (dimensionless)
μ_g	CO_2 viscosity (Pa s)
V	Darcy velocity (m/s)
σ_{go}	Interfacial tension between oil and CO_2 (N/m)
w_{C_i}	Weight fraction of composition i (dimensionless)
k	Permeability (mD)
Ø	Porosity (fraction)

Introduction

CO_2 injection is one of the most utilized, in most cases cost-effective, and popular methods used for pressure maintenance and EOR in sandstone oil reservoirs (Alvarado and Manrique 2010). In the past 5 decades, there have been extensive laboratory studies, numerical simulations, and field applications of CO_2 EOR processes (Alipour Tabrizy 2012; Arshad et al. 2009; Ghasemi et al. 2017; Godec et al. 2011; Gozalpour et al. 2005; Holm and Josendal 1974; Jarrel et al. 2002; Jianbo et al. 2016; Koottungal 2014; Kuuskraa and Koperna 2006; Mohammed-Singh and Ashok 2005). The most important mechanisms affecting oil displacement using CO_2 injection include oil swelling, reduction in oil viscosity, and interfacial tension (IFT) reduction (Holm and Josendal 1974; Jarrel et al. 2002; Orr Jr et al. 1982). Displacement efficiency of CO_2 flooding in porous media at immiscible condition is affected by the oil and CO_2 density

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difference, wetting properties of fluids, viscosity ratio of fluids, reservoir pressure and temperature, oil composition, and the rate of CO_2 injection (Holm and Josendal 1974). These parameters can be categorized into various dimensionless numbers, which provide appropriate tools to analyze different mechanisms such as capillarity, gravity, miscibility, and mobility in the porous media during the gas injection.

The effect of dimensionless groups on the oil recovery factor was investigated by Kulkarni and Rao (2006) using the results of miscible and immiscible CO_2 gravity drainage experiments. Wood et al. (2006) used dimensionless numbers to describe CO_2 flooding in a dipping, waterflooded reservoir. Dimensionless numbers were introduced for designing a series of experiments to develop screening criteria applicable to Gulf Coast reservoirs. Trivedi and Babadagli (2008) proposed a new group including the matrix-fracture diffusion transfer for scaling of the miscible displacement in fractured porous media. Rostami et al. (2010) conducted a series of forced gravity drainage experiments using a wide range of physical and operational conditions. Their results showed that use of each number alone is inadequate to obtain an acceptable correlation to predict recovery. They proposed a group of dimensionless numbers to provide an acceptable correlation with recovery.

Alipour Tabrizy (2014) investigated CO_2 EOR in sandstone and chalk rocks. The results show that a higher Bond number has a positive effect on oil recovery but there are limitations to capillary number performance. Eventually, Alipour Tabrizy introduced a dimensionless group to analyze the effect of parameters such as permeability, injection rate, capillarity, and CO_2 diffusion on the oil recovery factor. Rostami et al. (2018) conducted a complete series of PVT tests and core-flooding experiments in sandstones to investigate the effects of injectant type, reservoir pressure, and injection rate. The results show that oil swelling and oil viscosity reduction are the most effective parameters during gas injection in high permeable porous media saturated with semi-heavy oil. A new correlation, composed of empirical dimensionless numbers, was also proposed by results of core-flooding experiments, to predict oil recovery in heavy oil reservoir under gas flooding. Also, several studies have been carried out by researchers to predict the ultimate recovery of the oil fields which are under CO_2 injection. Data mining methods were used to develop dimensionless numbers that are able to predict oil recovery (Srivastava et al. 2016; Talluru and Wu 2017).

Some key parameters were neglected in some of papers mentioned above and this affects the accuracy of the oil recovery prediction, especially during immiscible-CO_2 flooding. On the other hand, taking into account all of the parameters makes the correlation complex and a lot of input data are required for oil recovery prediction. Hence, a comprehensive analysis of immiscible-CO_2 flooding in sandstone lithology is required to select all of the main governing parameters and develop new dimensionless numbers to predict the oil recovery factor.

The objective of this paper is to study the governing parameters affecting the performance of immiscible CO_2 flooding in sandstone core samples. A dataset of CO_2 core-flooding experiments was provided with a wide range of permeability, porosity, IFT, CO_2 injection pressure, and injection rate. These parameters have been analyzed to develop parametric numbers such as capillary number (N_c), relative radius (R_r) as a ratio of pore throat radius-to-core sample radius, pressure ratio of injection pressure and minimum miscibility pressure (P_r), and oil composition number (OCN). A new correlation based on the developed dimensionless groups was proposed to predict the oil recovery by CO_2 flooding at the core scale by combining the effects of different parameters such as porosity, permeability, capillarity, injection rate, injection pressure, and type of crude oil.

Methodology

Dataset

In this work, the parameters affecting ultimate oil recovery during CO_2 core flooding are categorized into operational parameters and rock/fluid properties. Parameters such as injection pressure, minimum miscibility pressure (MMP), temperature, and CO_2 injection flow rate are categorized in the former group and porosity, permeability, rock lithology, viscosity and density of crude oil and CO_2, IFT, and composition of crude oil are considered in the properties group. The results of various immiscible CO_2 flooding experiments at the core scale were collected to cover wide ranges of the mentioned parameters. As the aim of this paper is to develop a correlation for immiscible CO_2 flooding in sandstones, the lithology of the porous media and the state of injection, attempts were made to keep the parameters the same in all experiments. The range of the collected data is shown in Table 1 (Cao and Gu 2013; Kazemi et al. 2015; Khosravi et al. 2014, 2015; Nobakht et al. 2007; Norouzi et al. 2018; Shyeh-Yung 1991; Wang and Gu 2011).

Key parameters

The application of dimensionless numbers provides a way to scale and reduce the dimensionality of the dataset to analyze a phenomena more easily. This approach is widely used in reservoir engineering to analyze the governing forces and mechanisms during fluid flow in porous media. Also, the performance of different operational conditions and recovery scenarios can be compared. The mechanisms behind different recovery methods are studied by analyzing the relative

Table 1 Range of used parameters

Parameters	Range
Porosity (%)	10.8–37.2
Permeability (mD)	1–18,000
Lithology	Sandstone
CO_2 viscosity (Pa s)	1.36E−5–1.01E−4
Interfacial tension (N/m)	0.001–0.017
Injection rate (cm^3/min)	0.1–1.0
Injection pressure (MPa)	2.73–13.79
Core inclination	Horizontal
Temperature (°C)	27–80

importance of driving forces, such as viscous and capillary forces, in the form of dimensionless numbers. There are different definitions of the dimensionless variables in the literature (Abrams 1975; Alipour Tabrizy 2014; Brownell and Katz 1947; Dombrowski and Brownell 1954; Foster 1973; Green and Willhite 1998; Kulkarni and Rao 2006; Moore and Slobod 1955; Pennell et al. 1996; Rostami et al. 2010, 2018; Srivastava et al. 2016; Talluru and Wu 2017; Trivedi and Babadagli 2008; Wood et al. 2006). Our analysis showed that four different dimensionless numbers describe the physics of CO_2 flooding in porous media and can be used to predict the oil recovery. These parameters are capillary number (N_c), relative radius (R_r), injection pressure ratio (P_r), and oil composition number (OCN).

The capillary number shows the competition between viscous force and capillary force in the porous media during the course of an immiscible displacement, which is defined by Eq. 1 in our study.

$$N_c = \frac{\mu_g V}{\sigma_{go}} \tag{1}$$

where N_c is the dimensionless capillary number, μ_g is dynamic viscosity (Pa.s), V is Darcy velocity (m/s), and σ_{go} is interfacial tension between oil and CO_2 (N/m). Capillary number is a representative of the main forces during immiscible CO_2 flooding into horizontal cores. The large viscous force, developed by high-rate gas flooding, is characterized by large capillary numbers which leads to an unstable front and oil bypassing/trapping. However, low-rate gas flooding or high IFT may lead to considerable residual oil, as the pressure drop across the core cannot overcome the capillary threshold in the pores. Hence, different conditions of fluid flow in porous media emphasize the importance of N_c on accurately predicting oil recovery during CO_2 flooding.

Hydrocarbon storage capacity and deliverability indicate the quality of a porous media. The hydrocarbon storage capacity is characterized by the effective porosity, whereas the deliverability of porous media is a function of the permeability. Routine core analysis can provide these two parameters. Data obtained from core provided information on pore geometry, based on a modified Kozeny–Carmen equation and the concept of mean hydraulic radius (Amaefule et al. 1993). In this study, a dimensionless number is defined as a ratio of the pore throat radius-to-core sample radius. The value of relative radius (R_r) shown in Eq. 2, is a good indicator of a physical properties of rock that strongly affects oil recovery factor during CO_2 core flooding.

$$R_r = 3.14 \times 10^{-6} \frac{\left(\frac{k}{\varnothing}\right)^{0.5}}{\frac{d}{2}} \tag{2}$$

where R_r is relative radius (dimensionless), k is permeability (mD), $\varnothing$ is porosity (fraction), and d is core diameter (cm).

Interactions between the injected gas and oil directly depend on the state of injection (immiscible, near miscible, and miscible). For example, the effect of injection rate is significant in the near-miscible condition, while a lower injection rate results in more chance of multiple contact miscibility (MCM). Pressure difference between injection pressure and minimum miscibility pressure (MMP) shows the state of injection. In the immiscible condition (where injection pressure is lower than MMP), injection pressure plays an important role in altering the ultimate recovery of CO_2 core flooding (Li et al. 2017). Injection at pressure values closer to MMP affects the oil recovery and hence, in this study, the pressure ratio number (P_r) considers the effect of operational conditions. This pressure ratio is the ratio of injection pressure-to-minimum miscibility pressure as defined by Eq. 3.

$$P_r = \frac{P_i}{\mathrm{MMP}} \tag{3}$$

where P_r is injection pressure ratio (dimensionless), P_i is injection pressure (MPa), and MMP is minimum miscibility pressure (MPa).

As already mentioned, the most important mechanism in the immiscible CO_2 flooding process is oil viscosity reduction due to the dissolution of CO_2 in the crude oil. The solubility of CO_2 is a function of crude oil composition, operational pressure and temperature values. Hence, crude oil composition plays an important role in changing the ultimate oil recovery by immiscible CO_2 flooding (Holm and Josendal 1974; Li et al. 2013). Also, composition of oil affects the extraction and vaporization mechanisms during MCM (Holm and Josendal 1974). Preliminary analysis showed that the effect of heavier components in the oil affects recovery more significantly. Hence, the effect of oil composition is considered in a developed dimensionless number called "oil composition number (OCN)" as shown in Eq. 4.

$$\mathrm{OCN} = \sum_{i=10}^{n} w_{C_i} \tag{4}$$

where OCN is the dimensionless oil composition number and w_{C_i} is the weight fraction of composition i (dimensionless).

Results and discussion

For all of the tests in our dataset, we calculated proposed dimensionless numbers to find an appropriate correlation between oil recovery factor and each number. Figure 1 shows the relation of recovery factor and capillary number for different CO_2 core-flooding experiments on a semi-logarithm plot. Different flow regimes are expected for systems without gravity depending on the capillary number. For very slow displacements, the displacement is controlled by the heterogeneity of the capillary pressures along the interface. The capillary fingering regime is observed in such a system. For fast displacements, where viscous forces overcome capillary effects, a viscous fingering regime is observed, with a rapid breakthrough of the non-wetting fluid into the wetting fluid. As can be seen in Fig. 1, a higher capillary number leads to a higher oil recovery factor. This means that reduction in capillary force mobilizes the remaining oil in porous media, which decreases the trapping phenomena.

As mentioned before, relative radius is a good indicator of a rock's physical properties. Figures 2 and 3 show the results of relative radius versus oil recovery factor for two low and high relative radius ranges. Since the relative radius represents the ratio of the microscopic radius to the macroscopic radius, values with low relative radius indicate that porous media consist of pores with a small throat size, compared to an area open to flow. This means that the porous media has low quality and will be faced with fluid flow problems, such as hydrocarbon trapping. Otherwise, reported oil recovery factor is high for some cases

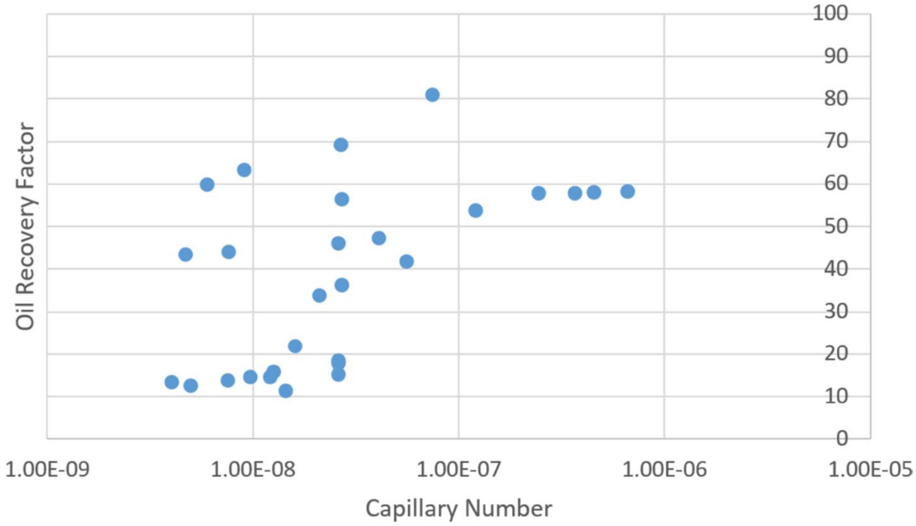


Fig. 1 Capillary number of CO_2 core-flooding tests

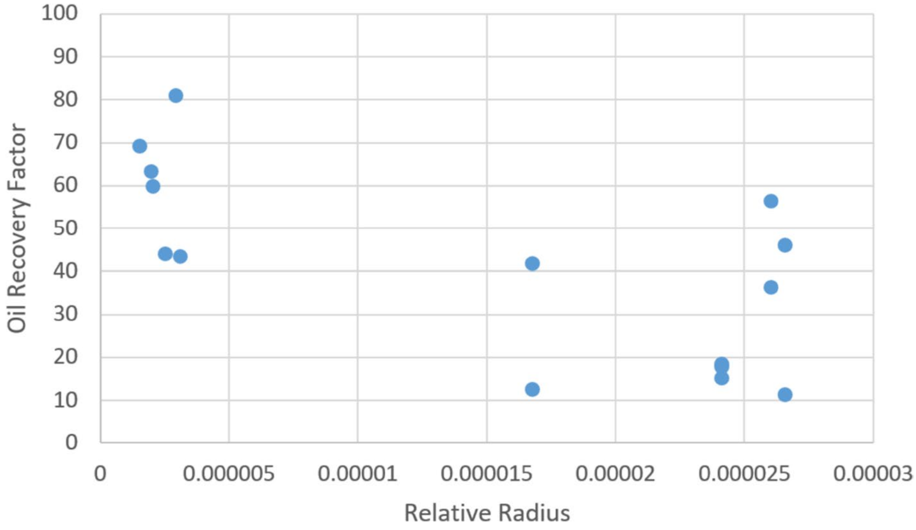


Fig. 2 Relative radius values for low-quality category of porous media

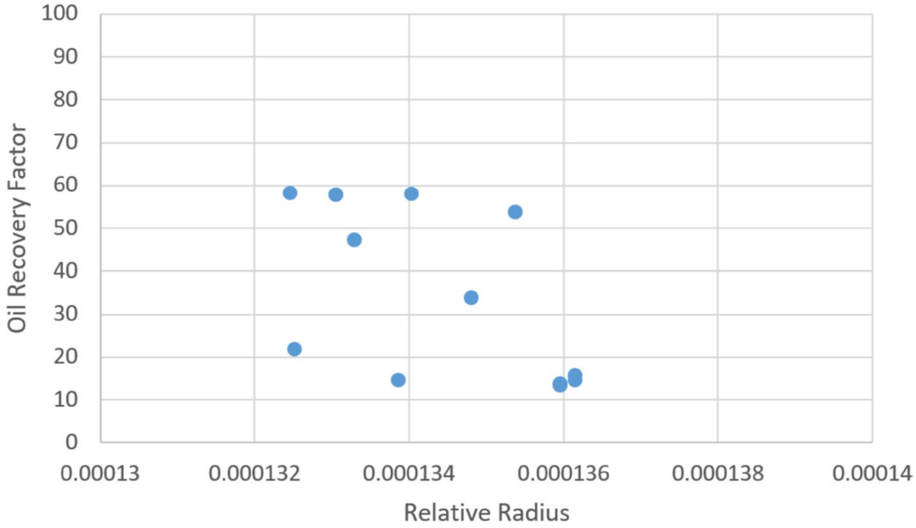


Fig. 3 Relative radius values for high-quality category of porous media

in this category. A high relative radius category leads to better physical quality of porous media, so it is expected that the fluid will flow more easily. It is obvious that there is no clear trend in the reported data, therefore effective parameters should be analyzed together.

Figure 4 depicts oil recovery factor versus injection pressure ratio values. As can be seen, higher pressure ratios result in higher oil recovery factor. This observation comes from the fact that miscible CO_2 flooding is subjected to a higher oil recovery factor compared to immiscible CO_2 flooding. In the higher pressure ratios (the values close to 1), partial miscibility occurs between the oil and CO_2 phase results in the CO_2 dissolution into oil phase. Dissolution of CO_2 contributes to oil production, as it reduces oil viscosity and capillary pressure. It also causes swelling of the oil, which increases oil saturation in the pore space and subsequently the relative permeability of the oil. All of the mentioned mechanisms improve oil recovery factor during immiscible-CO_2 flooding.

OCN values are presented in Fig. 5. These values are arranged versus oil recovery factor. Three ranges of OCN values have been selected in this study. The first range of OCN values covers the crude oil samples where 0.65 of their compositions consists of components with a carbon number of 10 and higher. This range is a good representative of light oil. In the second range of OCN values, the fraction of C_{10} and heavier hydrocarbons is 0.80–0.85. This range represents moderate oil. The third range covers heavy oil with a carbon number of 10 and higher. The results demonstrate that there is no clear trend between OCN and oil recovery factor; however, crude oil with lower OCN is expected to have more potential to be recovered.

The results presented in the above figures showed that a single dimensionless number could not forecast the oil production

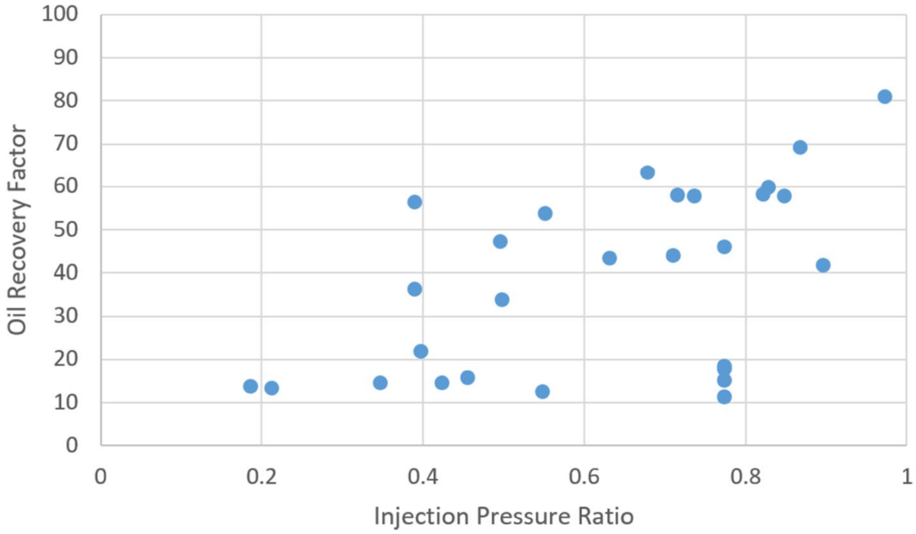
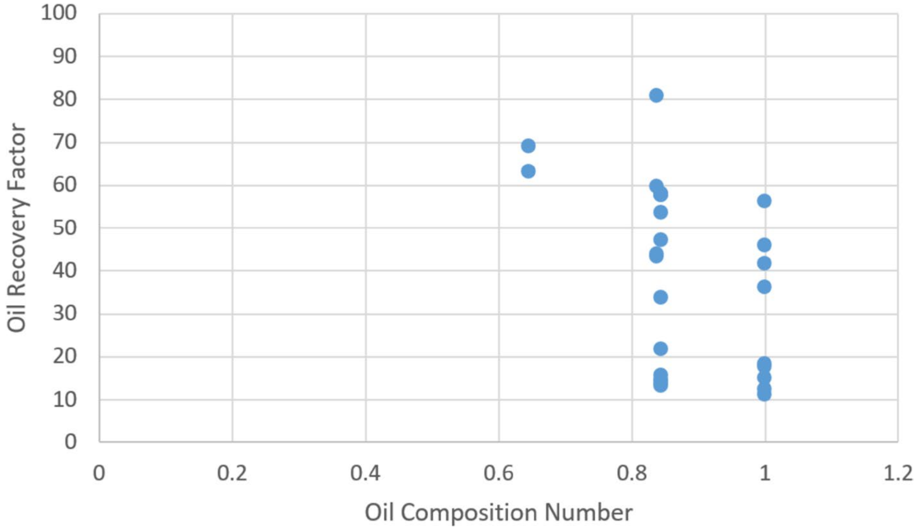


Fig. 4 Injection pressure ratio for CO_2 core-flooding tests

Fig. 5 Oil composition number for CO_2 core-flooding tests



characteristics during immiscible CO_2 core flooding due to the complexity of fluid flow in porous media. A combination of rock/fluid properties and operational conditions is needed to predict the oil recovery factor. Hence, a new approach is required to develop a relationship between oil recovery and operational and rock/fluid dimensionless numbers. Analysis using nonlinear regression was applied using programming code. The results of the analysis suggest a combined dimensionless number that consists of the capillary number and injection pressure ratio in the form of a fraction, with relative radius and oil composition number in the denominator. Equation 5 depicts the proposed combined dimensionless numbers.

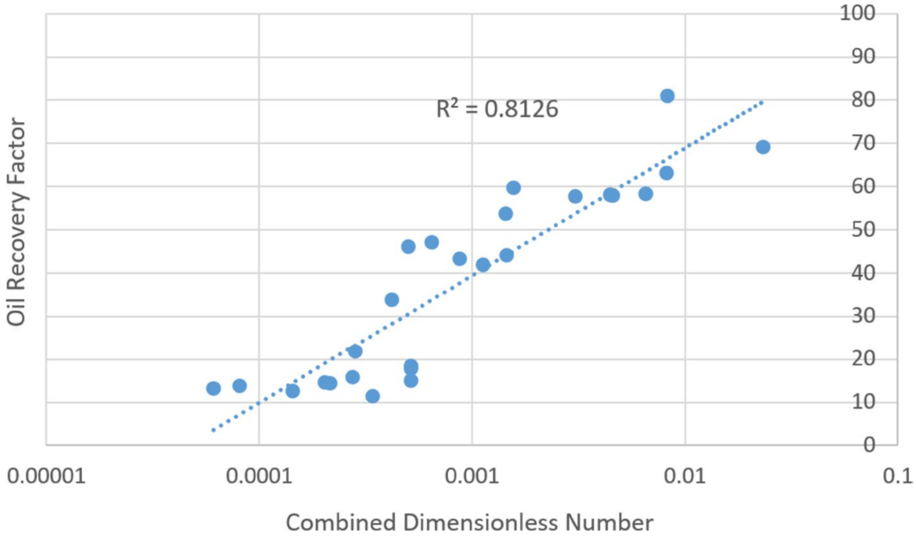
$$N_{\mathrm{Co}} = \frac{N_{\mathrm{c}}^{0.65} \times P_{\mathrm{r}}}{R_{\mathrm{r}}^{0.38} \times \mathrm{OCN}^{6}} \tag{5}$$

where the subscript Co stands for the term combined. A correlation has been developed based on N_{Co} and its corresponding experimental oil recovery factor for predicting oil recovery factor. Equation 6 shows the correlation that was developed and it follows the natural logarithm equations from the exponential models family.

$$\mathrm{ORF} = 12.806 \ln N_{\mathrm{Co}} + 127.87 \tag{6}$$

The results of the predicted oil recovery factor using combined dimensionless numbers and experimental immiscible-CO_2 flooding data are presented in Fig. 6 on a semi-logarithm plot. As can be seen, the proposed correlation can predict oil recovery factor with good agreement. The predicted oil recovery factor and experimental oil recovery factor are matched with 81% confidence. It shows that N_{Co} can be a good representation of the critical parameters that affect the results.

Fig. 6 Comparison of predicted oil recovery factor and experimental oil recovery factor



The significance of this study lies in the discovery that by incorporating rock/fluid properties and operational conditions, the accuracy of predicted oil recovery will be improved. Also, the capillary number connects all parameters and plays an important role in predicting oil recovery factor.

Conclusion

An accurate estimation of the oil recovery factor is required to analyze the performance of the method to design the EOR method successfully. In this study, a comprehensive analysis has been carried out to predict the oil recovery factor during the immiscible CO_2 flooding process. Hence, a new dimensionless number (relative radius) is suggested in this study to represent the ratio of pore throat radius-to-core sample radius, using permeability and porosity of the core samples. Additionally, the effects of oil quality and operational conditions were considered using the concept of injection pressure ratio and oil composition number. Also, a new correlation based on the developed dimensionless groups was proposed to predict the oil recovery by CO_2 flooding at the core scale. The results presented in this study suggested that capillary numbers, relative radius, injection pressure ratio, and oil composition number alone could not predict the oil production characteristics because there are a lot of forces and factors affecting oil recovery factor in porous media. To correlate the competition of forces in a porous media that eventually results in the oil recovery factor, a group of dimensionless numbers is needed that can handle a wide range of data. This allows a good correlation between oil recovery factor and the newly proposed group of dimensionless numbers used in this study. A logarithmic relationship was found between the proposed group and oil factor recovery. Predicted oil recovery factor shows good agreement with experimental data (with 81% confidence). This correlation is applicable for a wide range of porosity (10.8–37.2%), permeability (1–18,000 mD), injection pressure (2.73–11.44 MPa), injection rate (0.1–1.0 cm^3/min), and crude oil types.

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