A Comparison Study of the of the CO_2-Oil Physical Properties Literature Correlations Accuracy Using Visual Basic Modelling Technique

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PROFESSIONAL PAPER

A key parameter in a CO_2 flooding process is the gas solubility as it contributes to oil viscosity reduction and oil swelling, which together, in turn, enhance the oil mobility and oil relative permeability. Often injected gas-oil mixture physical properties parameters are established through time-consuming experimental means or using correlations available in the literature. However, one must recognise that such correlations for predicting the injected CO_2-oil physical properties are valid usually for certain data ranges or site-specific conditions.

In this paper, a comparison has been presented between the literature correlations for CO_2-oil physical properties using excel spreadsheet and also using Visual Basic soft ware. Emera and Sarma[6] correlations have yielded more accurate predictions with lower errors than the other tested models for all the tested physical properties (CO_2 solubility, oil swelling due to CO_2, CO_2-oil density, and CO_2-oil viscosity). Furthermore, unlike the literature models, which were applicable to only limited data ranges and conditions, Emera and Sarma models could be applied over a wider range and conditions.

The developed Visual Basic software can be used to test which correlation presents the best accuracy between a list of different literature correlations for CO_2-oil physical properties and then once the best correlation has been selected, the user can go to this correlation and use it in predicting the property (CO_2 solubility, oil swelling due to CO_2, CO_2-oil density, and CO_2-oil viscosity) when no experimental data are not available.

Key words: EOR, CO_2 flooding process, CO_2 solubility, density, viscosity

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 the natural pressure of the reservoir or gravity drive oil into the wellbore, combined with artificial lift techniques (such as pumps) which bring the oil to the surface. But 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 are generally include injecting water or gas to displace oil and drive it to a production wellbore, resulting in the recovery of 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 the introduction of heat such as the injection of steam to lower the viscosity of the heavy viscous oil, and improve its ability to flow through the reservoir.
- Gas injection, which uses gases such as natural gas, nitrogen, or carbon dioxide that expand in a reservoir to push additional oil to a production wellbore, or other gases that dissolve in the oil to lower its viscosity and improves its flow rate. 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.[8]

CO_2 flooding is an effective enhanced oil recovery process. It appeared in 1930's and had a great development in 1970's. Over 30 years' production practice, CO_2 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 (Hao, 2004).

CO_2 FLOODING

The phase behavior of CO_2 / crude- oil systems has been investigated extensively since the 1960'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 understanding the development, and prediction of the MMP for both pure and impure CO_2 injection have been ongoing for over thirty years. (Quinones et al, 1991)

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[17] 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 1 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.[11]

CO_2 Flooding process

Carbon dioxide injected into depleted oil reservoir with suitable characteristics can attain enhanced oil recovery through two processes, miscible or immiscible displacement. Miscible process is more efficient and most common in active enhanced oil recovery projects (Amarnath, 1999).

The following subsections explain the two processes, as follows:

Immiscible Displacement

In immiscible flooding, there exists an interface between the two fluids and thus, there also exists a capillary pressure caused by the interfacial tension between the oil and CO_2. The benefits of the flood are primarily due to reservoir pressure maintenance and by displacing the fluid. Since the two fluids are immiscible, higher residual oil saturations can be expected than with a miscible flood. Hence the immiscible flood achieves lower oil recoveries than the miscible flood. Whether a miscible or immiscible flood is to be implemented is dictated by the injection pressure and the MMP of the gas with the oil.[4]

Miscible Displacement

The CO_2 miscible process (First-Contact Miscible Process or Multiple-contact Miscibility process) shown in one such process (Fig.1). A volume of relatively pure CO_2 is injected to mobilize and displace residual oil. Through multiple contacts between the CO_2 and oil phase, intermediate and higher-molecular-weight hydrocarbons are extracted into the CO_2-rich phase. Under proper conditions which shown in (Table 1and Table 2), this CO_2-rich phase will reach a composition that is miscible with the original reservoir oil. From that point, miscible or near-miscible conditions exist at the displacing front interface (Green,et al.1998).There are two types of miscibility, first contact and multiple contact, as follows in table 1.

Table 1. Critical temperature of CO_2 and identified miscibility conditions. (Ahmad, 1997)

Criteria	Condition	Comments
$T_{res} < 30\ ^oC$	Immiscible	
$30\ ^oC < T_{res} < 32.2\ ^oC$	Miscible/Immiscible	Either possible $T_{CO2} = 31\ ^oC$
$T_{res} > 32.2\ ^oC$	Miscible possible	

Table 2. Critical pressure of CO_2 and identified miscibility conditions. (Ahmad, 1997)

Criteria	Condition	Comments
$p_{res} < 1\ 000$ psia	Immiscible	
$1\ 000$ psia $< p_{res} < 1\ 200$ psia	Miscible/Immiscible	Either possible $p_{CO2} = 1\ 073$ psia
$p_{res} > 1\ 200$ psia	Miscible possible	

The CO_2 –Oil Physical Properties Correlations

Knowledge of the physical and chemical interactions between CO_2 and reservoir oil in addition to their effect on oil recovery are very important for any gas flooding project. The major parameter that affects gas flooding is gas solubility in oil because it results in oil viscosity reduction and an increase in oil swelling, which in turn, enhances the oil mobility and increases the oil recovery

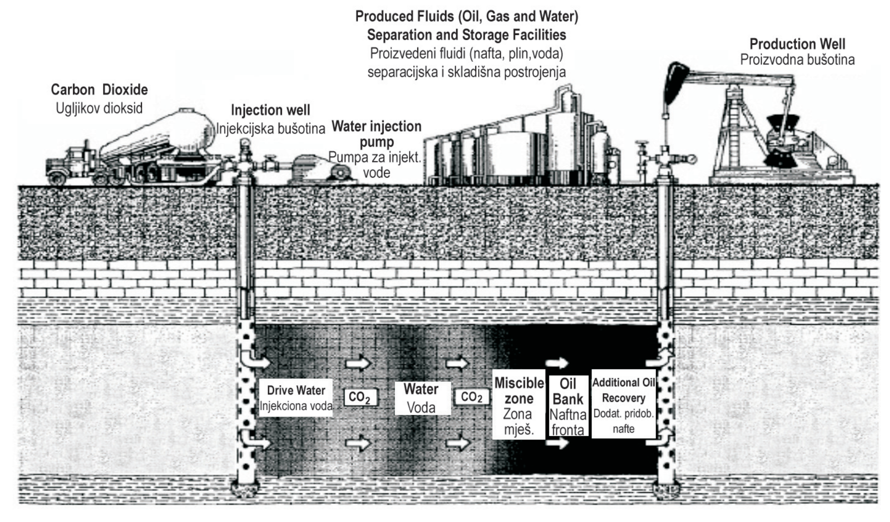

Fig. 1. CO_2 miscible process (Green and Willhite,1998).
Sl. 1. CO_2 miscibilni proces (Green and Willhite,1998)

efficiency. Therefore, a better understanding of this parameter and its effects on oil physical properties is vital to any successful CO_2 flooding project.

The injected gas effects on oil physical properties are determined by laboratory studies and available modelling packages. Laboratory studies are expensive and time consuming, particularly when one needs to cover a wider range of data. On the other hand, the available modelling packages can only be used in certain situations, and hence, may not be applicable in many situations.

Physical properties such as oil swelling due to CO_2, viscosity, density, and CO_2 solubility in oil are required to design and simulate oil recovery process. The effects of CO_2 on the physical properties of crude oils must be determined to design an effective immiscible displacement process. A predictive method of properties of heavy oil/CO_2 mixtures is useful for process design and screening. CO_2-oil Physical properties can be determined by two methods, experimental method and by correlations prediction.[3]

In this work, correlations were developed to predict the solubility of CO_2, swelling factor, viscosity of the CO_2/heavy-oil mixture, and density for models Emera and Sarma, (2006),Simon and Graue (1965) Mehrotra and Svrcek (1982) and Chung *et al.* (1986). The property-prediction package requires only the temperature, pressure, specific gravity of oil, and oil viscosity at any temperature and pressure condition to be entered.

CO_2 Solubility

As shown in Table 3 and Fig.2., the Emera and Sarma[6] offered a better accuracy compared to correlations of Simon and Graue (1965), Mehrotra and Svrcek (1982), and Chung *et al.* (1986). In addition to the higher accuracy and compared to the other available correlations, the Emera and Sarma[6] could be applied over a wider range of data conditions. Table 4 presents a summary of the experimental data range used in this study for testing of the CO_2 solubility in oil correlations.

Table 3. Comparison between the CO_2 solubility literature correlations

Correlations	No. of data	Average error, %	Stand. dev, %
Emera and sarma, (2006)	106	4.0	5.6
Simon and Graue (1965)	49	5.72	10.8
Mehrotra and Svrcek (1982)	106	32.6	36.6
Chung et al. (1986)	106	83.7	150.3

Table 4. Experimental data range used in this project for testing oil correlation

Variable	Minimum value	Maximum value
Saturation pressure ,(MPa)	0.5	27.4
Temperature, (ºC)	18.33	140
MW, (lb/mol)	196	490
Oil gravity, (API)	12	37.3

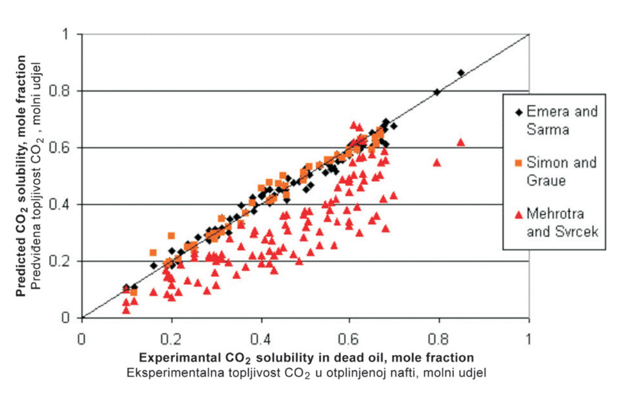

Fig. 2. Comparison results between Emera and Sarma[6] CO_2 solubility, Simon and Graue (1965), and Mehrotra and Svrcek (1982) correlations.

Sl. 2. Usporedba rezultata koralacije topivosti CO_2,između Emera and Sarma[6] i Simon i Grue (1965.) i Mehrotra and Svrcek (1982.)

Oil swelling factor

For the oil swelling factor, Table 5 and Fig. 3. present a comparison between the oil swelling factor correlations accuracy. As shown, the Emera and Sarma[6] model offered a better accuracy than that of Simon and Graue model. Also, it could be applied over a wider range of conditions. Table 6 presents a summary of the experimental data range used in this study for testing of the oil swelling factor (due to CO_2 injection) correlations.

Table 5. Comparison between different swelling factor correlations

Correlations	No. of data	Average error, %	Stand.dev, %
Emera and sarma (2006)	85	0.61	0.94
Simon and Graue (1965)	83	1.0	1.7

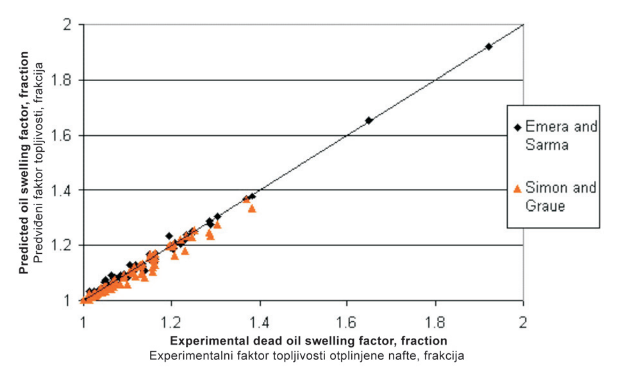

Fig 3. Comparison results between Emera and Sarma[6] and Simon and Graue (1965) oil swelling factor (due to CO_2) correlations prediction results

Sl. 3. Usporedba rezultata predviđene korelacije faktora topljivosti (zbog CO_2) nafte, između Emera and Sarma[6] i Simon and Graue (1965.)

Table 6. Experimental data range used in this study for testing of oil swelling factor (due to CO_2) correlations

Parameters	Minimum value	Maximum Value
Saturation pressure, (MPa)	0.1	27.4
Temperature, (ºC)	23	121.1
MW, (lb/mol)	205	463
Oil gravity, (API)	11.9	37.3

CO_2-oil Density

For the CO_2- oil density, as evident from Table 7 and Fig. 4, Emera and Sarma[6] model yielded a much lower error than the Quail *et al.* (1988) model. In addition, this model could be applied over a wider range of conditions. Table 8 presents a summary of the experimental data range used in this study for testing of the CO_2-oil density correlations.

Table 7. Comparison between Emera and Sarma[6] and Quail *et al.* (1988) correlations results for the CO_2- oil density prediction

Correlations	No. of data	Average Error, %	Stand.dev., %
Emera and Sarma (2006)	136	0.29	0.43
Quail *et al* (1988)	129	3.0	4.8

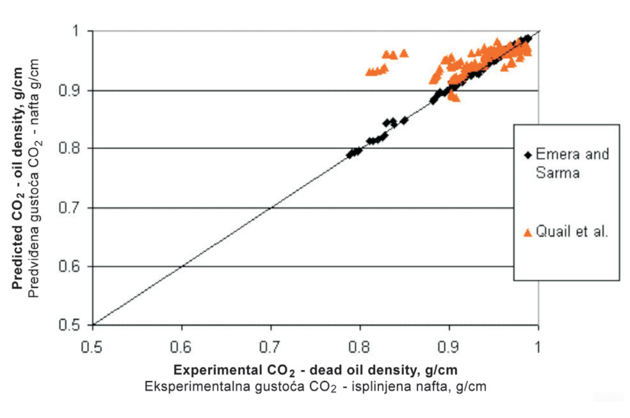

Fig. 4. Comparison results between Emera and Sarma[6] and Quail *et al.* (1988) CO_2- dead oil density correlations prediction results.

Sl. 4. Usporedba rezultata predviđene korelacije za gustoću mješavine CO_2 i isplinjene nafte, između Emera i Sarme[6] i Quaila i suradnika (1988.).

Table 8 . Experimental data range used in this study for testing of the CO_2- oil density correlations

Parameters	Minimum value	Maximum Value
Saturation pressure, (MPa)	0.1	34.5
Temperature, (ºC)	18.33	121.4
MW, (lb/mol)	246	490
Oil gravity, (API)	11.9	37.3
Initial density, (g/cm^3)	0.789	0.9678

CO_2-oil viscosity

For CO_2- oil viscosity, compared to other correlations (Beggs and Robinson (1975) and Mehrotra and Svrcek (1982), Emera and Sarma[6] CO_2- oil viscosity correlation appeared to yield more accurate results (see Table 9 and Fig. 5). Also, it could be used successfully for a wider range of conditions (e.g., has been applied for up to 12 086 mPa·s). Table 10 presents a summary of the experimental data range used in this study for testing of the CO_2- oil viscosity correlations.

Table 9. Comparison between CO_2- oil viscosity literature correlations

Correlations	No. of data	Average Error, %	Stand.dev %
Emera and Sarma (2006)	130	6.0	8.8
Beggs and Robinson (1975)	130	56.8	62.7
Mehrotra and Svrcek (1982)	130	94.3	95.2
Quail et al.(1988)	130	208.9	376.43

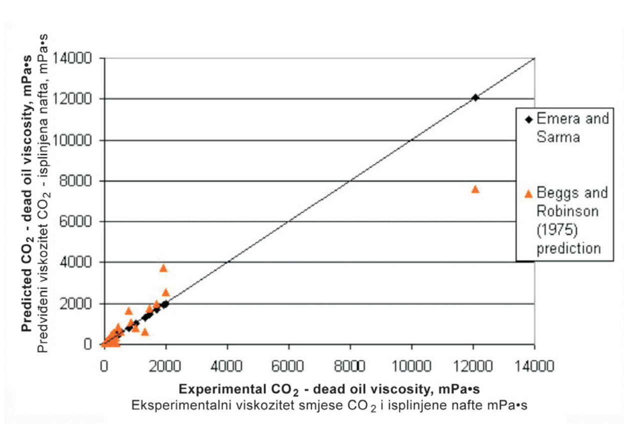

Fig. 5. Comparison results between Emera and Sarma[6] and Beggs and Robinson (1975) CO_2- dead oil viscosity correlations.

Sl. 5. Usporedba rezultata korelacije, Emera and Sarme[6] i Beggsa i Robinsona (1975), za korelaciju viskoznosti mješavine CO_2 i isplinjene nafte

Table 10. Experimental data range used in this study for testing of the CO_2- oil viscosity correlations

Parameters	Minimum value	Maximum Value
Saturation pressure, (MPa)	0.1	34.48
Temperature, (ºC)	21	140
MW, (lb/mol)	205	530
Oil gravity, (API)	10	37.3
Solubility, mole fraction	0.0	0.768

Recommendation and Conclusions

Visual Basic software was developed in this study and was successfully used as a comparison and predictive tool for CO_2-oil physical properties. This software has been tested and validated the comparison and property prediction using literature data sets.

Experimental data available in the public domain were used in testing of different CO_2-oil physical properties correlations. Based on the data used in this study and keeping in mind the limitations of this data, the following conclusions are made.

1. The Visual Basic software that has been developed in this study proved to be an efficient method in testing of the different literature models (CO_2 solubility, oil swelling factor, CO_2–oil density, and CO_2–oil viscosity). It can be used as a predictive tool to use certain literature correlation to predict the CO_2-oil physical properties.
2. Emera and Sarma[6] CO_2-oil mixture physical properties models prediction presented a more reliable prediction with higher accuracy than the other models tested in this study.
3. Besides the higher prediction results with better accuracy, Emera and Sarma[6] models were capable of covering a wider range of oil properties, with regard to oil gravities, pressures up to 34.5 MPa, oil MW>490 lb/mol, oil viscosities up to 12 000 mPa·s, and temperatures up to 140 °C.
4. In the absence of any measured site-specific interactions data and when the project financial situation is a concern, Emera and Sarma[6] correlations could be used as an effective predictive tool to guesstimate CO_2-oil physical properties for initial design calculations. They can be used as a fast track gas flooding project screening guide. In addition, they could contribute towards designing a more efficient and economical experimental programs.

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