Velocity and density of oil-HC-CO_2 miscible mixtures

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Summary

Due to differences in basic physical properties between CO_2 and hydrocarbon gases (HC) and oils, CO_2 has a significant impact on velocity and density of oil-HC-CO_2 miscible mixtures. We present measured velocity and density of oil-HC-CO_2 mixture at conditions of temperature from 40 to 100°C, pressure from 20 to 100MPa, and GOR up to 300L/L. Based on experimental data, preliminary velocity and density models for oil-HC-CO_2 miscible mixture are proposed.

Introduction

Miscible gas flooding is a well-known methodology for enhanced oil recovery. As carbon dioxide (CO_2) becomes a focal target for sequestration, applying CO_2 to enhance oil recovery is highly motivated. First, we have investigated velocity and density properties of miscible mixture of CO_2 with gas-free oil, in which CO_2 is fully dissolved into oil in a single phase. Due to differences of physical properties of CO_2 from oils, CO_2 has a significant impact on properties of the oil-CO_2 mixtures. Based on measured data, we have developed preliminary models for the velocity and density of the oil-CO_2 miscible mixture (Han et al., 2011). Since conventional "live" oil with dissolved hydrocarbon gases (oil-HC) is more common at in situ condition, we have to consider effect of CO_2 on properties of "live" oil when they are mixed. Properties of oil-HC-CO_2 mixture are influenced with different CO_2 saturations, which can be in HC-dominated or CO_2 dominated forms. With CO_2 as a major component, properties of oil-HC-CO_2 mixture cannot be directly estimated by using models for conventional "live" oil. On the other hand, when HC gas is a major component, the models for the oil-CO_2 mixture cannot be used either. Here in the second step, we investigate velocity and density properties of oil-HC-CO_2 mixture at in situ condition, and reveal how we can model them.

In this paper, we present measured velocity and density of oil-HC-CO_2 miscible mixture with temperature from 40°C to 100°C, pressure from 20 to 100MPa, and GOR up to 300L/L. Also, preliminary velocity and density models for oil-HC-CO_2 mixture are proposed based on experimental data.

Experimental design

Sample preparation

Based on the measured data of oil-CO_2 miscible mixtures, two more groups of samples are prepared to investigate velocity and density properties of oil-HC-CO_2 miscible mixtures.

Group 1 has three samples made by an oil with API gravity of 32.84 and different gases. Sample 1A is the oil dissolved with CO_2, that has GOR (CO_2 - oil volume ratio at the standard condition) 97.83L/L. The gas gravity of CO_2 is 1.5281. Sample 1B is the oil dissolved with hydrocarbon gas with GOR 201.91L/L. The gravity of the hydrocarbon gas used is 0.91118. Sample 1C is the oil dissolved CO_2 with GOR 97.83L/L and hydrocarbon gas with GOR of 201.91L/L. This group of samples is used to investigate effects of dissolved gas on oil properties of oil-HC-CO_2 mixture.

Group 2 has three samples with three oils dissolved with both CO_2 and HC gas. Sample 2A is an oil with API 23, and dissolved HC gas with GOR 205.75L/L and CO_2 with GOR 100.88L/L. Sample 2B is an oil with API 32.84, and dissolved HC gas with GOR 201.91L/L and CO_2 with GOR 100.86L/L; Sample 2C is an oil with API 39.81, and dissolved HC gas with GOR 102L/L and CO_2 with GOR 103L/L. This group of samples is used to investigate API gravity effects on oil properties of oil-HC-CO_2 mixture.

Experiment setup and procedure

For investigating CO_2 effect on "live" oil, the experimental instruments and the measurement procedures are the same as those used for studying oil-CO_2 miscible mixture presented at the 2011 SEG annual meeting (Han et al., 2011).

Experimental data and revealed physical properties

Property of the oil-HC-CO_2 miscible mixture is affected by the different properties of each component. Figure 1 shows velocity and density trends at various temperature and pressure conditions for oil (API 39.81), HC gas (Methane) and CO_2. Velocity and density of the oil are calculated by FLAG (a computer program developed by the Fluids/DHI consortium), and of CH_4 and CO_2 by NIST program. Since velocities of HC and CO_2 are much lower than those of oil,

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dissolved gas, either HC or CO_2, or their combination tends to reduce oil velocity. The higher gas-oil ratio (GOR) is, the lower velocity of oil-HC-CO_2 mixture becomes. Oil shows smallest temperature and pressure effect on density. CH_4 has much smaller density than the oil and CO_2 with high pressure effect, but low temperature effect. Dissolved HC gas will cause great reduction of oil density. But CO_2 shows significant different density properties from those of HC gas and oil, which is more sensitive to temperature and pressure effect. One more special feature is that densities of CO_2 are much higher than that of CH_4, and are overlapped with that of the oil. With increasing pressure, density of CO_2 may vary from lower than that of oil to higher. This feature has a significant effect on density of the oil with dissolved CO_2.

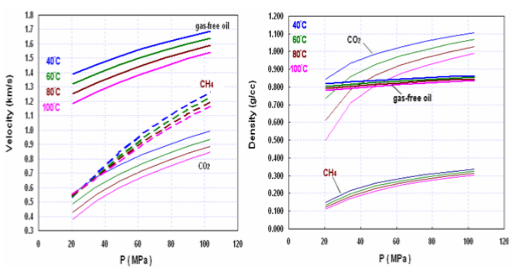

Figure 1. Velocity and density of the gas-free oil, CH_4 and CO_2.

Velocity

Measured data of the sample group 1 show that dissolved HC gas and CO_2 have different effects on oil velocities (Figure 2). Since velocities of HC are more sensitive to pressure, while velocities of CO_2 are more sensitive to temperature, velocities of oil dissolved with HC gas show a higher pressure trend than that of the oil. But velocities of oil with dissolved CO_2 remind a similar pressure trend as that of the oil. Velocities of oil dissolved with both HC gas and CO_2 show a combined pressure effect depending on their GORs. Similarly, dissolved HC gas and CO_2 effect on temperature trends of oil velocity can be observed. Therefore, with CO_2 dissolved into "live" oil, CO_2 effect on the oil velocities cannot be treated simply as that of HC gas dissolved in the oil.

The experimental result also reveals that the combined effect of dissolved HC gas and CO_2 on velocity cannot be simply modeled by an ideal liquid principle (Figure 2 and Figure 6). The combined HC-gas and CO_2 effect tends to be smaller than that of the simple additive effect on velocity. The data may reveal that HC gas and CO_2 dissolved in the oil cannot follow the ideal liquid principle. Different gases dissolved into oil with very different properties will cause different packing of molecules and deviated properties, such as velocity from the assumption of non-interaction for the ideal liquid principle.

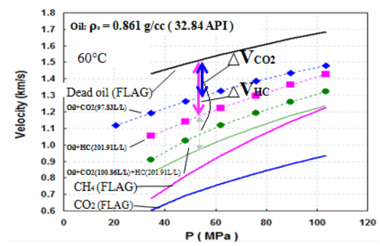

Figure 2. Measured velocity (symbols) compared with component velocities by FLAG.

Density

Figure 3 shows the experimental data compared with densities of gas-free oil. Within the experimental temperature and pressure conditions, data show that dissolved CO_2 increases density of the oil, while dissolved HC gas decreases density of the oil. Therefore, density of "live" oil becomes more complicated with CO_2 injection.

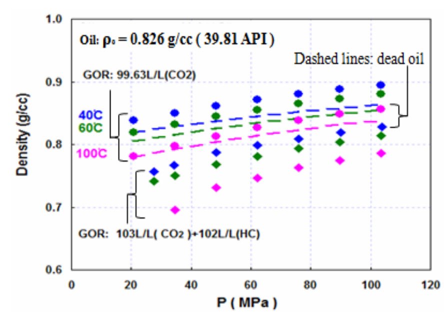

Figure 3. Measured densities of oil-CO_2 mixture and oil-HC-CO_2 mixture compared with densities of dead oil (sample 2C).

Obviously, the much higher density of CO_2 leads to important impedance differences between CO_2 dissolved oil and HC dissolved oil. Hence dissolved CO_2 significantly affects oil's acoustic property at in-situ condition (Figure 4).

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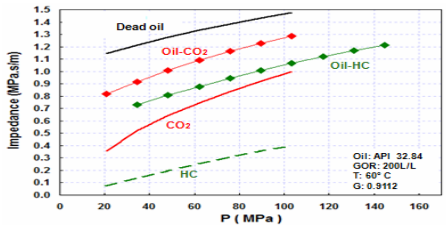

Figure 4. Impedance comparison.

Modeling

Based on our experimental results, preliminary models of velocity and density are proposed for conventional oil within data limitation, where $40 \le T \le 100^{\circ} C$, $20 \le P \le 100 MPa$, and GOR<300L/L.

Velocity model

Velocity properties of oil with dissolved HC gas and CO_2 are dependant on oil API, GOR and gas gravity of HC and CO_2, and in-situ temperature and pressure condition. Because of the different velocity trends of HC and CO_2 with temperature and pressure, effect of dissolved CO_2 on oil properties cannot be simply treated as effect of dissolved HC that we have modeled in the FLAG program. Even more complicated as mentioned previously, combined effects of dissolved HC gas and CO_2 cannot simply utilize a kind of average approach similar as ideal liquid principle. In the example shown in Figure 2, velocities of oil dissolved with HC gas and CO_2 show underestimated pressure effect if treating CO_2 as HC gas. On the other hand, if simply adding CO_2 effect to velocity of the oil with dissolved HC gas, velocity of the oil will be overestimated.

A new model is proposed by integrating of our existing velocity models of oil-HC and oil-CO_2. However the interaction among of oil, HC and CO_2 must be considered. The new model can be expressed as

$$V = V_{oil\_HC} - \Delta V_{oil\_CO_2} + C_{oil\_HC\_CO_2} \qquad (1)$$

Where, V is velocity of the oil with both dissolved HC gas and CO_2;

V_{oil_HC} is velocity of oil with dissolved hydrocarbon gas (HC) and it can be estimated by FLAG;

$\Delta V_{oil\_CO_2}$ is velocity reduction with dissolved CO_2 and it can be estimated by

$$\Delta V_{oil\_CO_2} = V_{dead\_oil} - V_{oil\_CO_2}. \qquad (2)$$

Where V_{dead_oil} is velocity of gas-free oil calculated by FLAG. $V_{oil\_CO_2}$ is velocity of oil with dissolved CO_2, and it can be obtained by the velocity model of oil-CO2 miscible mixture (Han et al., 2011). $C_{oil\_HC\_CO_2}$ is a correlation to describe physical interaction when oil is dissolved with HC gas and CO_2, and it is a function of oil's API and CO_2's GOR,

$$C_{oil\_HC\_CO_2} = C_{\rho_0} C_{GOR}. \qquad (3)$$

Where $C_{\rho_0} = 1.6457\rho_0 - 1.3174$ is a correlation for oil with deferent API as measured data shown in Figure 5,

and $C_{GOR} = \frac{GOR_{CO_2}}{600}[1 + \frac{500}{GOR_{CO_2}+1}]$ is a correlation for oil with deferent GOR of CO_2.

The estimated results by the new model are presented in Figure 6, and they are matching the measured data well. The figure also shows that velocities of oil with dissolved HC gas and CO_2 are overestimated if treating CO_2 effect as that of HC gas, and underestimated if utilizing the CO_2 effect on velocity of oil with only dissolved CO_2.

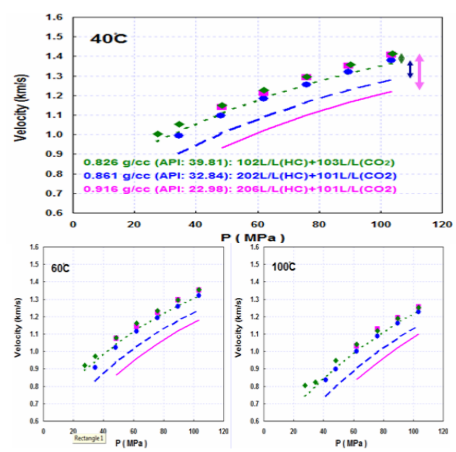

Figure 5. Measured velocities of oil-HC-CO_2 mixtures with deferent APIs for investigating API correlation.

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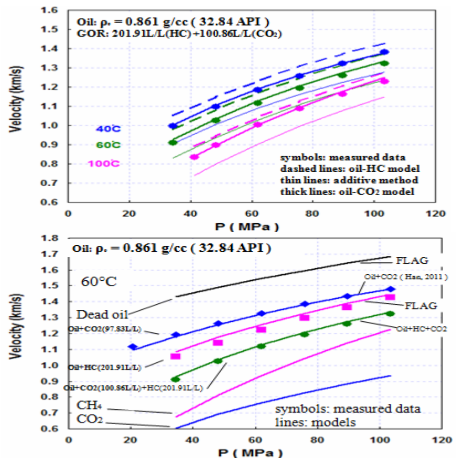

Figure 6. Measured velocities of oil-HC-CO_2 mixture compared with predicted results by models.

Density

Since the density of CO_2 is much higher than that of HC, and overlapped with density of oil, CO_2 dissolved in oil causes complexity of density properties of oil. The model of the oil with dissolved HC gas underestimates CO_2 effect, and the simple additive method ignores interaction when both HC gas, and CO_2 dissolved into the oil. We have found that the modified density model for oil-CO_2 mixture (Han et al., 2011) can be used to estimate densities of the oil-HC-CO_2 mixture. The Modified model is still a kind of linear volume average one as

$$\rho = f_{v\_co_2}\rho_{e\_co_2} + f_{v\_oil\_HC}\rho_{oil\_HC} \quad (4)$$

The parameter $\rho_{e\text{-}co2}$ is the effective density of CO_2 which is defined and can be calculated by the density model of oil-CO_2 mixture,

$$\rho_{e\_co_2} = c_1 + c_2T + c_3\left(\frac{1-c_4^{\ P}}{1-c_4}\right) + c_5TP \quad (5)$$

where T is temperature in degree C, P is pressure in MPa, and the coefficients $c_1 = 0.86476$, $c_2 = -0.001982$, $c_3 = 0.0074$, $c_4 = 0.9794$, and $c_5 = 7.4*10^{-8}$.

$\rho_{oil\text{-}HC}$ is density of live oil calculated using the FLAG program. $f_{v\_co_2}$ *and* $f_{v\_oil\_HC}$ are volume fractions of CO_2 and "live" oil component at given pressure and temperature conditions, respectively. They can be estimated by

$$f_{v\_co_2} = \frac{M_{co_2}/\rho_{e\_co_2}}{1+M_{co_2}/\rho_{e\_co_2}} \quad (6)$$

and

$$f_{v\_oil\_HC} = \frac{1}{1+M_{co_2}/\rho_{e\_co_2}} \quad (7)$$

with $M_{co_2} = 0.001868866 GOR_{CO_2}$.

Figures 7 demonstrates comparison of the models with experimental data. It is obvious that the HC model and the simply additive method cannot make correct prediction. The new model is much better for describing density properties of oil-HC-CO_2 mixtures.

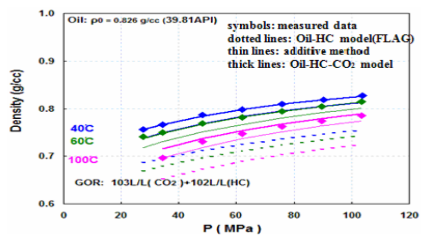

Figure 7. Measured densities of oil-HC-CO_2 mixture compared with predicted results by models.

Conclusions

Velocity and density of oil-HC-CO_2 miscible mixture were measured at in-situ temperature and pressure conditions, $40 \le T \le 100^\circ C$, $20 \le P \le 100MPa$, and *GOR<300L/L*. Their properties are dependent on oil API, HC and CO_2 percentage, GOR, gas gravity, and in-situ temperature and pressure conditions.

Different physical properties of HC and CO_2 significantly affect velocity and density properties of oil-HC-CO_2 mixture, which cannot simply be treated as oil-HC mixture or be estimated by applying the ideal liquid principle.

Dissolved CO_2 significantly affects oil's acoustic property at in-situ condition.

Preliminary models of velocity and density for oil-HC-CO_2 mixture were developed within investigated conditions. The predicted results by models match the measured data well.

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EDITED REFERENCES

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