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The Effect of Pressure and Porous Media Structural Parameters Coupling on Gas Apparent Viscosity

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Abstract

Crude oil production is still considered a significant contributor to global energy security. To improve oil production, gases such as CH_4, N_2, Air and CO_2 are injected into oil reservoirs in a process called gas Enhanced Oil Recovery (EOR). Authors have used several engineering, geological and geometrical quantities to characterise oil reservoirs and evaluate immiscible gas EOR processes. Viscosity is one of such critical engineering quantities. However, the relationships between viscosity and structural parameters, such as porosity, pore size, and aspect ratio, have not been directly investigated in the literature. This paper investigated the coupling effect of pressure and structural parameters on the apparent viscosity of EOR gases in reservoir pore matrix through rigorous data mining and experimental approaches. The data mining analyses demonstrated that EOR reservoirs are characterized by viscosity and porosity. The experimental investigation indicated that the viscosity of injected EOR gases increases with pressure and pore size, decreases with porosity, and initially decreases before increasing with aspect ratio. The study concluded that CO_2 is the most influenced by porosity, and CH_4 is the least. Furthermore, N_2 is the most responsive to pore size and aspect ratio, while CH_4 is the least responsive.

Keywords: Viscosity, reservoir characterisation, porosity, pore size, EOR gases

1. Introduction

Viscosity is a measure of the fluid resistance to flow when a shearing force is applied to the fluid [1,2,3]. In Enhanced Oil Recovery (EOR), viscosity is considered the single most important fluid property that lends itself to the estimation of other engineering quantities such as pressure drop, displacement velocity, momentum, diffusibility, kinetic energy, interfacial tension, capillary number, flowrate, mobility and viscous ratios, [4,5]. Furthermore, viscosity is featured as a critical quantity in all EOR screening models found in the literature [6,7,8,9].

The displacement of oil by another fluid involves the interactions between the displacing fluid and oil's viscosities and the interactions with other reservoir properties such as pressure and structural parameters. Gases such as CO_2, N_2, CH_4 and Air are some of the fluids injected into oil reservoirs pore to displace trapped oil [10,11]. Unfortunately, oil is about 100 times more viscous than these gases [12], and reservoirs are usually structurally heterogeneous. Therefore, a need to understand the interactions. Previous authors have sparsely studied the effect of pressure and temperature on fluid viscosity in the context of EOR gases in reservoir pore matrix [12,13,14]. Furthermore, the impact of reservoir structural parameters such as porosity, pore size, and aspect ratio on EOR gas viscosity and the consequential effect on gas-oil displacement performance is lacking in the literature. Consequently, this study aims to characterize the apparent viscosity of reservoir oils and the EOR gases used to displace the oils.

Furthermore, the study investigated the coupling effect of pressure and reservoir structural parameters on the competitiveness of EOR gas viscosity.

2. Methods and Materials

The methodology applied two rigorous empirical approaches:

1. Data mining of field data from 484 EOR projects. Cluster, Coefficient of Variation (CV), Set theory, and range were applied to the field data to characterise and determine the criticality, sensitivity and redundancy of the reservoir parameters of interest (viscosity, porosity, pore size, aspect ratio).
2. Data analyses of gas experiments, comprising five reservoir analogue core samples, four gases, and eight isobars, to characterise EOR gases and determine the effect the structural parameters have on the viscosity profiles of the respective EOR gases.

2.1. Data Acquisition

For the data mining, data for viscosity, porosity, pore size, and aspect ratio were directly acquired from the records of the collated field data. Where such a record is missing, correlational equations were used to estimate the missing values from other parameters present in the database.

For the gas experiments, established equations for states were directly used or modified to estimate values for viscosity, porosity, and aspect ratios.

The viscosity, μ, was acquired using gas and radially modified the Hagen-Poiseuille equation. The traditional Hagen-Poiseuille equation is expressed in Eq. (1) in a linear flow form through a straight pipe of capillary, where Q_c is the capillary volumetric flowrate, $cm^3.s^{-1}$; r_c is the capillary radius, cm; dP is the differential pressure across the capillary, $dyne.cm^{-2}$; μ is the fluid viscosity, poises, and l_c is the length of capillary, cm. The negative coefficient is due to the flow being in the direction of diminishing pressure.

$$Q_c = -\frac{\pi {r_c}^4}{8\mu}\left(\frac{dP}{dl_c}\right) \quad 1$$

For a flow through a pipe or capillary with a radius, r_c, the fluid entrant area is:

$$A = \pi r^2 \quad 2$$

Substitute the entrant area in Eq. (2) for Eq. (1)

$$Q = \frac{A^2}{8\pi\mu}\left(\frac{dP}{dr}\right) \quad 3$$

For a configuration with stacks of capillaries forming a radial geometry, the area, A, available for fluid entrance is related to an effective height, h, and the geometric radius, r of the stack:

$$A = 2\pi rh \quad 4$$

The radial area can substitute the linear area in Eq. (3):

$$Q = -\frac{\pi h^2 r^2}{2\mu}\left(\frac{dP}{dr}\right) \quad 5$$

For an isothermal flow where the quantities are measured at the output Q_2, the outlet flow rate to atmospheric pressure, P_2, the following gas equation holds:

$$QP = Q_1 P_1 = Q_2 P_2 \quad 6$$

Substituting for Q in relation to the output:

$$Q_2 P_2 = -\frac{\pi h^2 r^2}{2\mu}\frac{PdP}{dr} \quad 7$$

Rearrange and integrate with respect to pressure and flow path:

$$\int Q_2 \frac{dr}{r^2} = -\int \frac{\pi h^2}{2\mu}\frac{PdP}{P_2} \quad 8$$

Integrating both sides of the equation and applying the boundary conditions of pressure and radial length in the direction of flow resolve the negative coefficient on the right side and generate a new negative coefficient on the left side due to the direction of flow towards diminishing radial boundaries. It would cancel out when $\left(\frac{1}{r_1}-\frac{1}{r_2}\right)$ is operated on because the outer radius r_1 is larger than the inner radius r_2.

$$-Q_2\left(\frac{1}{r_1}-\frac{1}{r_2}\right)=\frac{\pi h^2}{4\mu}\frac{({P_1}^2-{P_2}^2)}{P_2} \qquad 9$$

Make viscosity the subject of the formula in Eq.9:

$$\mu = -\frac{\pi h}{4Q_2P_2}\left(\frac{{P_1}^2-{P_2}^2}{\left(\frac{1}{r_1}-\frac{1}{r_2}\right)}\right) \qquad 10$$

The porosities of the respective cores were acquired using Eq. (11). Pore sizes are as stated by the sample's manufacturer. The aspect ratio is as estimated by Eq. (13).

$$Porosity = 1-\left(\frac{Specific\ Particle\ Density}{Specific\ Bulk\ Density}\right) \qquad 11$$

$$Pore\ size = \text{as}\ supplied\ by\ core\ sampled\ manufacturer \qquad 12$$

$$Aspect\ ratio = \left(\frac{Pore\ diameter}{radial\ thickness}\right) \qquad 13$$

2.2. Experimental Procedure

a. The core samples were secured in a stainless core holder containing an inlet (for gas feed) and outlet (for gas permeate).
b. The core set was maintained at a temperature of 20C.
c. Inject gas into the core holder at a set pressure (start pressure: 0.20Bar)
d. Measured outlet flowrate, temperature and pressure when the steady-state flow is achieved.
e. Repeated steps a-c at intervals of 0.40bar until the maximum pressure (3bar) is reached.

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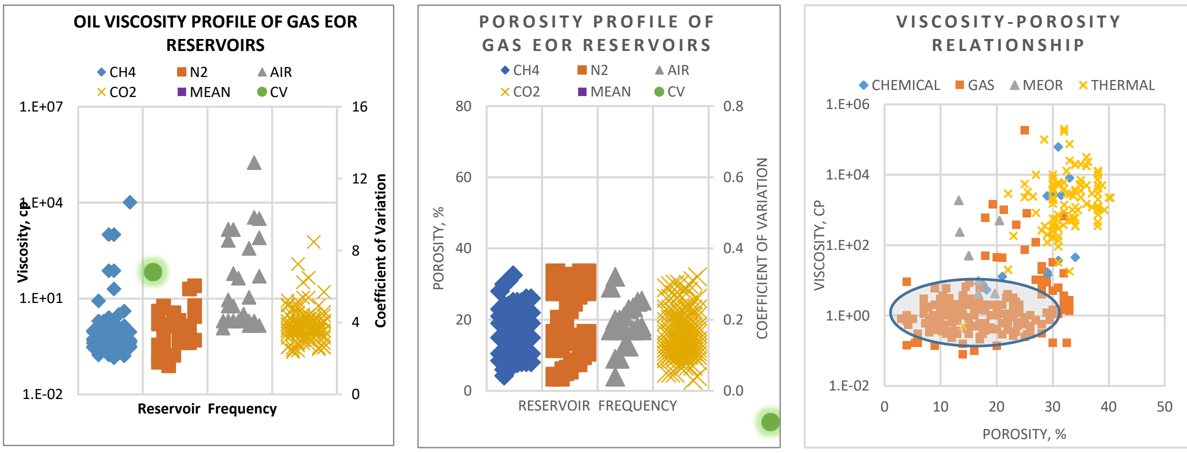
3. Conclusions

The study has contributed to engineering knowledge and reservoir practices as follows: It has been demonstrated that EOR technologies and Gas processes are markedly characterised by viscosity (Figure 1a) and slightly characterised by porosity (Figure 1b). It is established in Figure 1a that CH_4 and N_2 EOR processes favour relatively low viscosity reservoirs than Air and CO_2 processes. The Coefficient of Variation (CV) indicates that N_2 has the tightest clusters, suggesting that viscosity may be critical to the applicability and performance of N_2 EOR processes in a reservoir.

The study presented a strong relationship between viscosity and porosity for gas EOR technology, as shown by the grey cluster in Figure 1c. This relationship reveals that gas EOR is commonly applied to tight reservoirs. Furthermore, the findings from the data mining phase (Figure 1a, b, and c) provided an impetus for designing a gas experiment to examine and validate the field application of immiscible gas EOR.

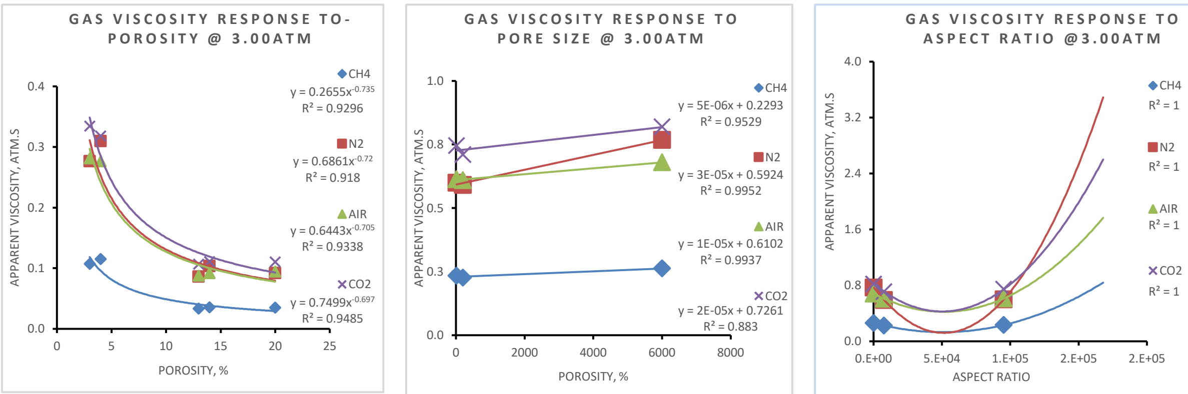


a. b. c.

Figure 1 Showing the viscosity (a) and Porosity (b) characterisation, and the viscosity-porosity relationship (c) of EOR reservoirs

In the experimental phase, it has been identified that porosity inversely affects apparent viscosity under certain conditions of porosity <20% and pressure >1.4bar (Figure 2a). Beyond this threshold, the slope of the plot starts to disappear, indicating that the viscosity becomes self-sufficient of pressure and porosity. Hence, any change in porosity and pressure have an insignificant or no effect on the apparent viscosities of the EOR gases. As porosity approach unity, the gas viscosity for N_2, Air, and CO_2 appears to approach equality except for CH_4. By the nature of the respective gas plots in Figure 2a, it can be concluded that CH_4 is the least competitive in attaining the desirable condition of mobility (<1) mentioned in [15] and favourable apparent viscosity ratio (<1) for any coupled pressure and porosity.

Figure 2b shows that N_2 is consistently the most responsive to pore size variation in reservoirs. In contrast, CH_4 is the least. Their respective thermodynamic properties cannot explain the order of the magnitude of the slopes.



a. b. c.

Figure 2 Showing the viscosity-porosity (a) viscosity-pore size (b) viscosity-aspect ratio (c) relationships of EOR gases.

Figure 2c shows a quadratic relation exists for the apparent viscosity-aspect ratio. Before attaining the aspect ratio of $5.00x10^4$, the relationship is inverse but becomes positive after that point. For all isobars, N_2 is consistently more responsive to aspect ratio than the other gases. In contrast, CH_4 is the least responsive.

Summatively, it is concluded that N_2 viscosity responds to reservoir structural parameters than the other EOR gases. This information is useful for selection and managing the injection of gases and the displacement expectation of trapped oil in a reservoir with structural variation (heterogeneity).

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