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Experimental Evaluation of the Mobility Profile of Enhanced Oil Recovery Gases

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Abstract

The mobility profiles of gases used in enhanced oil recovery (EOR) have been thoroughly investigated through the coupling operations of data mining of oilfield data and experimental data analyses. Mobility as an EOR objective function has not been previously applied to characterize potential reservoirs for EOR selection and application, even though it is a robust combinatorial function that benefits from two petrophysical variables, permeability and viscosity. The data mining approach identified mobility as a reliable objective function for reservoir characterisation. The data distribution and clustering results indicate that Gas EOR reservoirs have relatively higher mean mobility than Thermal, Microbial and Chemical EOR reservoirs. The experimental approach investigated EOR gases, CO_2, CH_4, N_2, and Air. A modified Darcy Equation of State for gas flow through porous media was applied to evaluate which gas would competitively attain the oil displacement optimisation criterion for mobility ratio, $M \leq 1$. Coupling the data mining with the experimental data results reveals that gas reservoirs can be further categorized by mobility. CH_4 (18.16 mD/cp) was observed to have the highest mobility followed by Air (14.60 mD/cp), N_2 (13.61 mD/cp), and CO_2 (12.96 mD/cp). The gas mobility order significantly corresponds with the mobility distribution of reservoirs that implemented gas EOR processes. It was concluded that CO_2 offers relatively lower mobility, therefore, it is the most competitive EOR gas to approach the mobility ratio criterion of unity or less.

Keywords

Mobility, Viscosity, Permeability, Oil, Gas, Reservoir Characterization, EOR Displacement

1. Introduction

One of the key objectives of reservoir engineering is to identify which Enhanced

Oil Recovery (EOR) process is capable of displacing and producing the most oil. For over 6 decades, gases such as CO_2, CH_4, N_2, and Air have been injected into reservoirs to displace trapped oil ([1] [2] [3] [4] [5]). However, different gases may exhibit certain flow pressure, volume, temperature (PVT) behaviour that could improve or inhibit their EOR potential and efficiency. Therefore, understanding the behaviour of the respective EOR gases would enable engineers to effectively compare their EOR suitability and oil recovery prospect in a reservoir of interest. Consequently, this study aimed to evaluate and identify the competitiveness of EOR gases in displacing trapped oil.

The state of art of gas EOR also indicates that several authors have investigated different parameters that affect oil recovery. References [1] [2] [3] [4] have indicated that relative mobility and viscosity ratios are essential factors to be considered in displacing trapped oil. Several authors have statistically applied different petrophysical parameters and properties to characterise EOR reservoirs and evaluate their effect on the application and performances of EOR technologies. Reference [4] [6]-[13] have mentioned parameters such as permeability, API° gravity and viscosity as suitable parameters for characterising EOR reservoirs. Few authors also included porosity and reservoir thickness as useful parameters ([5] [14]-[19]). In all these EOR criteria, the authors have not investigated the effect of combinatorial quantities, such as mobility, momentum and transmissibility, in characterising EOR reservoirs and screening criteria. Although some other authors have carried out experiments to evaluate gas EOR potential. Such authors include [20]-[25]. However, their studies were conducted on a single or two gases basis (usually CH_4 or CO_2), thereby missing the opportunity for comparing and contrasting the broad spectrum of EOR gases with respect to gas properties, such as viscosity and molecular weight, and reservoir parameters, such as pore size and heterogeneity and mobility. There is no study robust enough to compare the four common EOR gases on these fronts. Therefore, it is imperative to study these two areas of EOR with respect to the relative performance of the four gases used in EOR projects and the mobility profile of the reservoirs they will be applied to. Consequently, this study aims to tackle the knowledge gap and provide statistical and experimental solutions in EOR gas selection, application and potential.

Two empirical approaches have been applied in the evaluation. These are data mining and experimental methods as used by authors such as [1] [2] [8] [26].

2. Approach 1: Oilfield Data Analyses

Data mining tools were applied on 365 EOR projects to identify critical EOR and reservoirs parameters that can be used to characterise EOR reservoirs and facilitate the design of laboratory experiments to evaluate EOR gases competitiveness. The benefit of this approach is that it provides insight into the state of the art of EOR technologies across the world and transfer trends from field operation to design laboratory experiments. Information from the data mining phase was useful in executing the experimental phase. This data mining technique has been effectively applied in previous work by authors such as [2].

Data Mining Results and Discussions

Reference [8] [17] and [18], have mentioned API gravity, viscosity, permeability, and depth as engineering quantities for evaluating EOR process competitiveness. It was however observed through data mining that intrinsic mobility M_i was a more robust reservoir factor for characterising EOR reservoirs and evaluating EOR applicability and potential. This factor is derived from Equation (1). Unlike the other parameters, mobility is a combinatorial quantity that combines a rock parameter (permeability K_i, mD) and a fluid property (dynamic viscosity μ_i, cp). Where "*I*" can be gas or oil fluid, the mobility of the fluid and reservoir system is given as:

$$M_i = \frac{K_i}{\mu_i} = \left(\frac{K}{\mu}\right)_i \tag{1}$$

The Mobility equation in Equation (1) was applied to the collated field data to generate reservoir characterization clusters in **Figure 1**. It is observed that EOR reservoirs form different clusters around four EOR technologies. It also reveals that the mobility ratio distribution for gas EOR has relatively higher mean values (628 D/cp) than the other EOR technologies, such as Chemical (36.36 mD/cp), Thermal (11.98 mD/cp) and Microbial EOR (7.31 mD/cp) technologies. The implication is that the most applicable EOR methods for such reservoirs are within the Gas EOR technology domain.

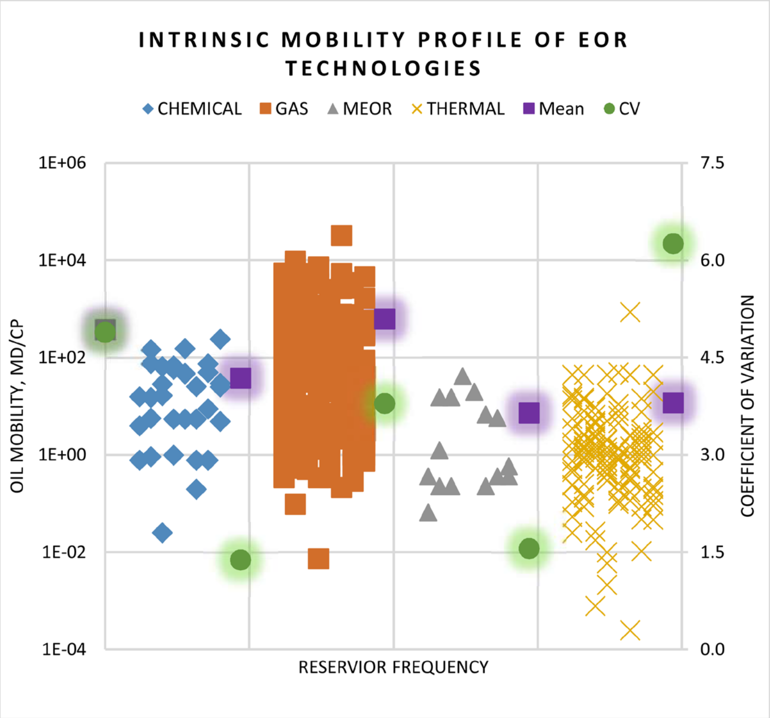


Figure 1. Characterisation of global EOR reservoirs by the intrinsic mobility of oil.

However, gas EOR technology has more than one method (Miscible and Immiscible) and gases (CO_2, CH_4, N_2, and Air). Consequently, the next stage of the study was to identify the characterisation of the reservoirs and the competitiveness of the gases with respect to immiscible Gas EOR technology.

Reference [2] stated that EOR displacement efficiency is based on the dimensionless quantity known as Relative Mobility Ratio, *M*. For immiscible gas EOR, *M* is the ratio of oil mobility, M_o, to gas mobility, M_g ([27] [28] [29]), this is shown in Equation (2).

$$M = \frac{M_{displaced}}{M_{displacing}} = \frac{M_o}{M_g} = \left(\frac{\left(\frac{K}{\mu} \right)_o}{\left(\frac{K}{\mu} \right)_g} \right) \quad (2)$$

Reference [30] [31] and Warner, and Holstein (2007) and Muggeridge *et al.*, (2014) emphasized that to achieve stable and favourable oil displacement, M must be ≤1. When M is >1, it implies that the displacing fluid (gas) is more mobile than the displaced fluid (oil). This will cause the oil to be bypassed by the stream of gas, thereby creating an unstable front, undesired viscous fingering, resulting in significantly poor sweep efficiency ([1] [31] [32] [33]). **Figures 2(a)-(c)** show three scenarios of oil-gas mobility ratios. The gas is injected into the injection well, oil and gas are expected at the producer well. A stable contour in A and B optimize oil production, while **Figure 2(c)** maximizes gas production because of the relatively higher mobility ratio (M = 2.40).

Consequent to **Figure 1** and **Figure 2(a)** and **Figure 2(b)**, Approach two of this study was therefore designed to identify the gas that would comparatively approach M ≤ 1. A modified Darcy equation of state (Equation (3)) for gas radial flow at varying temperature was used to derive intrinsic mobility of the respective gases.

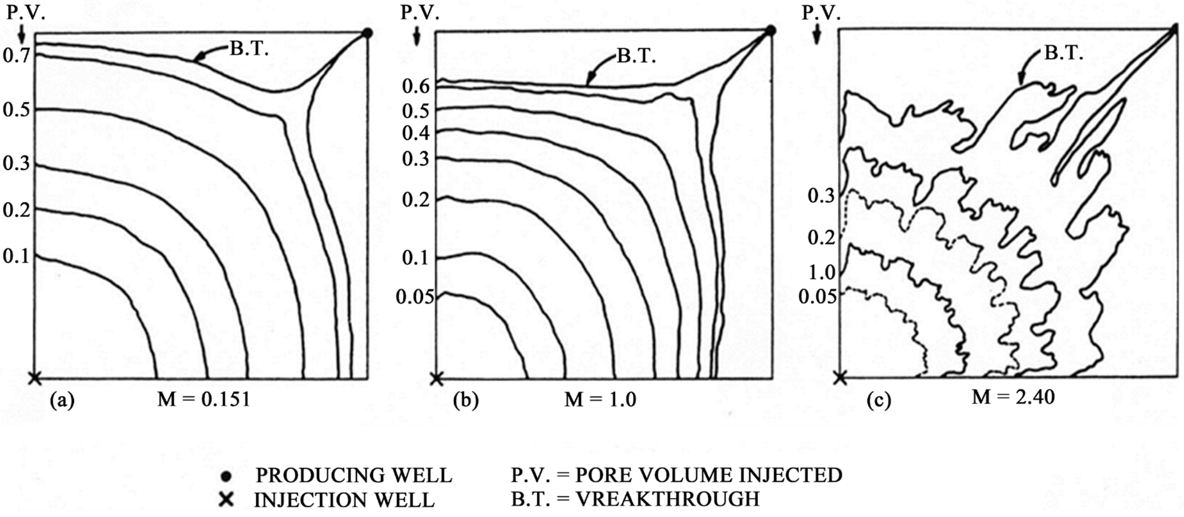


Figure 2. Areal view of the effect of mobility ratio on gas/oil displacement process [30].

$$Q_{std}=920\frac{K}{\mu}\frac{\left(P_1^2-P_2^{\ 2}\right)}{\ln\frac{r_1}{r_2}}\frac{MC_p}{\left(\mathrm{H}+MC_pT_1\right)} \tag{3}$$

In a comparative study to investigate energy transfer between injected gases at T_1, and core sample (or reservoir) possessing heat energy, H, the First and Second thermodynamics laws lend themselves to understanding how the energy transfer could be described with respect to specific heat at constant pressure, C_p, of the respective gases. The temperature of the injected gases, T_1, could be considered as a convenient constant injection reference temperature (standard, 273 K, or normal, 293 K) and the heat supplied to the core sample can be maintained as a steady heat supply. Therefore, without loss of generality, T_1 and H can be eliminated as a constant in Equation (3), thereby reducing the equation to an apparent flow shown in Equation (4):

$$Q_{std-apparent}=\frac{K}{\mu}MC_p\left(P_1^2-P_2^{\ 2}\right) \tag{4}$$

Consequently, the respective intrinsic mobility of the gases can be expressed as:

$$\mathrm{M}_i=\left(\frac{K}{\mu}\right)_i=\left(\frac{Q_{std-apparent}}{MC_p\left(P_1^2-P_2^{\ 2}\right)}\right)_i \tag{5}$$

3. Approach 2: Laboratory Experimental Analyses

Laboratory PVT experiment and analyses in analogous reservoir conditions were carried out using mobility as the EOR objective function as identified in Approach one.

3.1. Experimental Materials and Equipment Set up

1) Five Core Samples with pore sizes: 15 nm (x2), 200 nm (x1) and 6000 nm (x2).
2) Four EOR Gases: CH_4, N_2, Air, CO_2.
3) **Figure 3** shows the equipment and setup of the experiment.

3.2. Experimental Procedure

1) The core holder was heated to the desired temperature and thermal stability.
2) Gas was supplied into the core holder set up to the desired pressure.
3) Flow rate readings were recorded at a steady state.
4) This procedure is repeated at pressure intervals of 0.40 bar until the maximum pressure (3 bar) and temperatures 293, 323, 373, 423, 473 and 673 K are reached.

3.3. Experimental Results and Discussions

Experimental data were applied to Equation (5) to generate the intrinsic mobilities of the respective gases. The data so generated was used to make cluster plots.

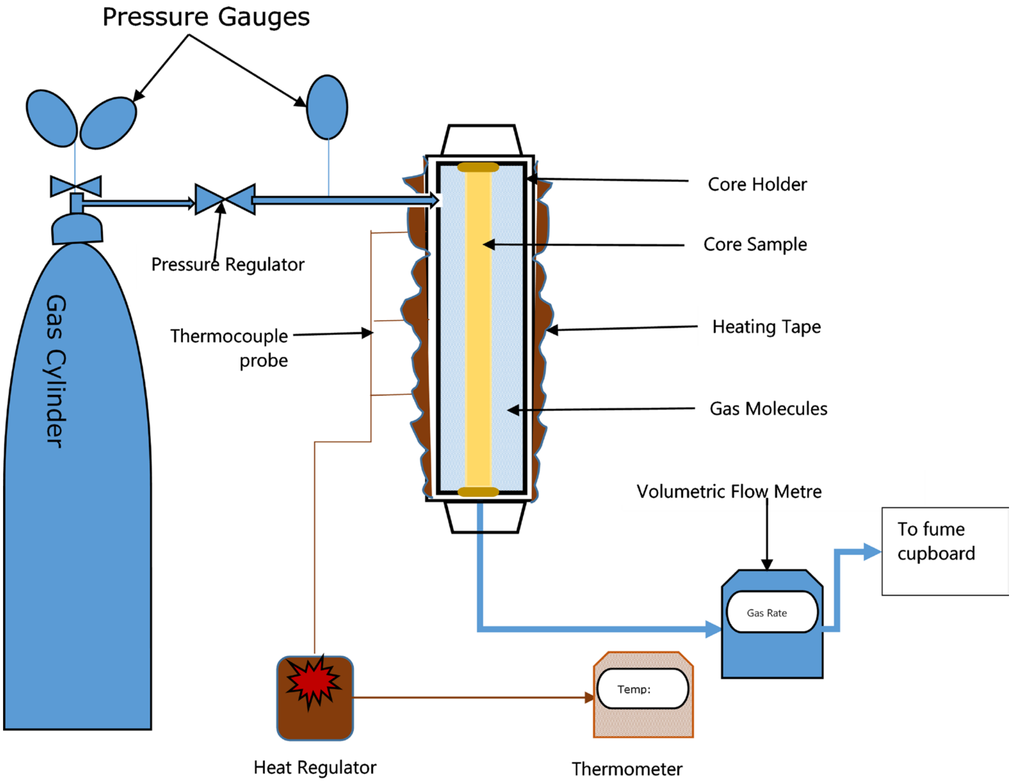
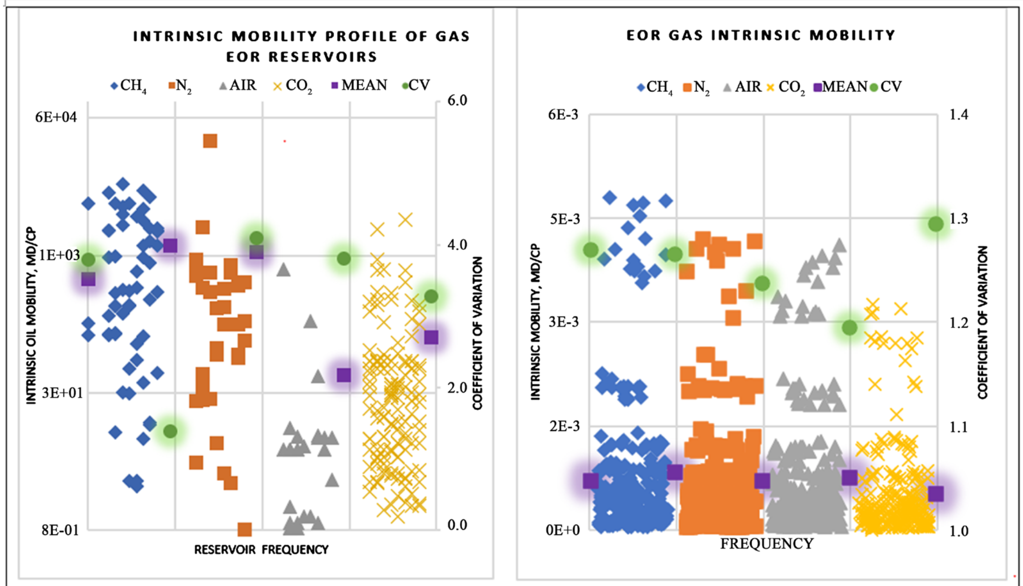


Figure 3. A schematic of experimental equipment and set up.

The field and experimental results were compared and summarized in Figure 4(a) and Figure 4(b). It was discovered from the clusters that reservoirs with relatively high intrinsic mobility (>1650 mD/cp) implemented CH_4 (18.16 mD/cp) gas EOR. In contrast, reservoirs with relatively low mobility (<121 mD/cp) implemented CO_2 (12.97 mD/cp) gas EOR. The cluster for each of the gases in Figure 4(b) is seen to have three sub-clusters. The topmost clusters in Figure 4(b) significantly correspond with the order of the clusters in Figure 4(a). Therefore, the apparent intrinsic mobilities in Figure 4(b) can be said to correspond with and validates the experimental mobility of EOR gases in Figure 4(a). CH_4 (18.16 mD/cp) was observed to have the highest mobility followed by Air (14.60 mD/cp), N_2 (13.61 mD/cp), and CO_2 (12.96 mD/cp).

These results are very revealing because this relationship has not been reported in journals previously. Although the mobilities clusters of Figure 4(a) and Figure 4(b) correspond, however, based on the relative mobility ratio criteria earlier stated by [1] [31] [32] and [33], it is expected that CO_2 will be the most likely gas to approach the favourable condition of $M \leq 1$, therefore the most competitive EOR gas. It is also noted that the CVs for the graphs are fairly opposite in direction. The gas EOR reservoirs CVs form a convex profile, while the displacing gas CVs form a concave profile. This suggests that in the implementation of gas EOR injection in reservoirs, the observed sensitivity of the respective gas mobilities in the laboratory may not have a significant effect on implementation.

EOR process sensitivity to mobility can be compared in **Figure 5**. The relative magnitude of the field and experiment data indicates the field and experimental



a) The reservoirs are characterised by intrinsic mobility, such that CH_4 clusters settles at the higher mobility reservoirs than CO_2. The order of the CV distribution indicates CH_4 is the most likely to be perturbed mobility variation and N_2 is the least perturbed.

b) The clusters are well defined and distinct, indicating that EOR gases can be characterised by mobility. The order of magnitude here is similar to that of reservoir oil mobility. This is implying a proportional correlation between gas and reservoir oil mobilities exists, although the order of the gas and oil CVs is shown to be inversely related.

Figure 4. Graphs comparing and contrasting the mobility profiles of global gas EOR reservoirs and projects (a) and the Mobility profile of EOR gases (a).

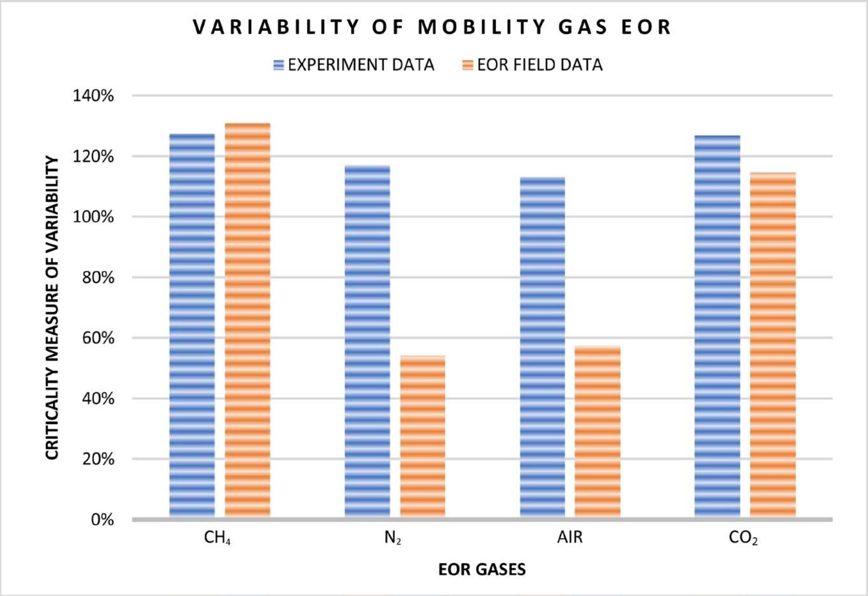


Figure 5. Variability of mobility in the field and experimental data.

data significantly validated each other. **Figure 5** shows that N_2 and Air are the most sensitive to mobility by virtue of their relatively low variability values.

4. Conclusions

Field and laboratory experimental data have been successfully applied to investigate the competitiveness of EOR gases based on the identified combinatorial objective function called intrinsic mobility.

It has been demonstrated that EOR projects and reservoirs can be characterized and evaluated based on intrinsic mobility. This characterisation is also reflected in the EOR gases commonly injected to displace trapped oil. The experimental results significantly validated the mobility profile observed in the field mobility clusters.

For the fours EOR gases, the experiments confirmed that CO_2 is the most competitive gas followed by N_2, Air and CH_4.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Q_g = *gas* flow rate ($cm^3.sec^{-1}$);

K_g = gas permeability (mD);

$K_=$ = oil permeability (mD);

μ_g = gas viscosity (cp);

μ_0 = oil viscosity (cp);

P_1 and P_2 = Inlet and outlet pressure (atm);

M = Molar mass (g/mol);

C_p = specific heat-constant pressure;

h = height of core sample (cm);

r_1 *and* r_2 = core inner and outer diameter (cm);

'i*'* = fluid such as gas and oil;

T_1 = Inlet temperature of gas;

PVT = Pressure, Volume and Temperature.