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Enhanced Oil Recovery by Miscible Flooding

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ABSTRACT─ Microscopic displacement efficiency is largely a function of interfacial forces acting between the oil, rock, and displacing fluid. If the interfacial tension between the trapped oil and the displacing fluid could be lower, the oil droplets could be deformed and could squeeze through the pore constrictions. A miscible process is one in which the interfacial tension is zero; that is, the displacing fluid and the residual oil mix to form one phase. If the interfacial tension is zero, then the capillary number (Nc) becomes infinite and the microscopic displacement efficiency is maximized. In this article have been investigated the effect of some parameters such as reservoir pressure , miscible gas density , oil density , initial water saturation and gas density on miscible flooding .

Keywords: Microscopic displacement, Interfacial force, Capillary number

Introduction

Miscible displacement processes are defined as processes where the effectiveness of displacement results primarily from miscibility between the oil in place and the injected fluid . Figure 1 is a schematic of a miscible process . Fluid A is injected into the formation and mixes with the crude oil , which forms oil bank . A mixing zone develops between fluid A and the oil bank and will grow due to dispersion . Fluid A is followed by fluid B, which is miscible with fluid A but not generally miscible with the oil and which is much cheaper than fluid A. A mixing zone will also be created at the fluid A and fluid B interface. It is important that the amount of fluid A that is injected be large enough that the two mixing zones do not come in contact . If the front of the fluid A and fluid B mixing zone reaches the rear of the fluid A and oil mixing zone, viscous fingering of fluid B through the oil could occur.
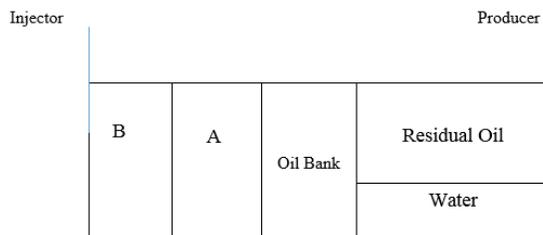

Figure 1: Schematic of Miscible Process

Consider a miscible process with *n*-decane as the residual oil, propane as fluid A, and methane as fluid B. The system pressure and temperature are 2000 psia and 100 °F , respectively. At these conditions both the *n*-decane and the propane exist as liquids and are therefore miscible in all proportions. The system temperature and pressure indicate that any mixture of methane and propane would be in the gas state; therefore, the methane and propane would be miscible in all proportions. However, the methane and *n*-decane would not be miscible for similar reasons. If the pressure were reduced to 1000 psia and the temperature held constant, the propane and *n*-decane would again be miscible. However, mixtures of methane and propane could be located in a two-phase region and would not lend themselves to a miscible displacement. Note that in this example the propane appears to act as a liquid when it is in the presence of n-decane and as a gas when it is in contact with methane. It is this unique capacity of propane and other intermediate gases that leads to the miscible process. There are, in general, two types of miscible processes. One is referred to as the single-contact miscible process and involves such injection fluids as liquefied petroleum gases (LPGs) and alcohols. The injected fluids are miscible with residual oil immediately on contact. The second type is the multiple-contact, or dynamic, miscible process. The injected fluids in this case are usually methane, inert fluids, or an enriched methane gas supplemented with a C2–C6 fraction. The injected fluid and oil are usually not miscible on first contact but rely on a process of chemical exchange between phases to achieve miscibility.

Single Contact Miscible Process

The phase behavior of hydrocarbon systems can be described with the use of ternary diagrams such as figure 2 . Researchers have shown that crude oil phase behavior can be represented reasonably well by three fractions of the crude. One fraction is methane (C1). A second fraction is a mixture of ethane through hexane (C2–C6). The third fraction is the remaining hydrocarbon species

lumped together and called C7+. Figure 2 illustrates the ternary phase diagram for a typical hydrocarbon system with these three pseudo components at the corners of the triangle. There are one-phase and two-phase regions in the diagram. The one-phase region may be vapor or liquid (to the left of the dashed line through the critical point *C*) or gas (to the right of the dashed line through the critical point). A gas could be mixed with either a liquid or a vapor in appropriate percentages and yield a miscible system. However, when liquid is mixed with a vapor, often the result is a composition in the two-phase region.
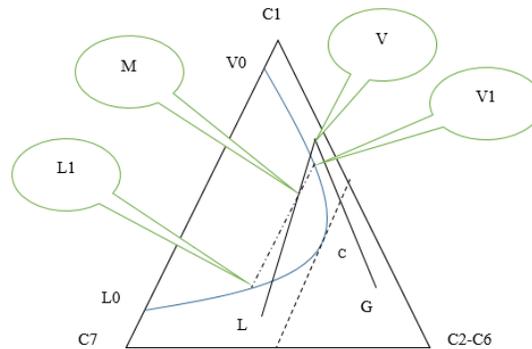

Figure 2 : Ternary diagram illustrating typical hydrocarbon phase behavior at constant temperature and pressure

A mixing process is represented on a ternary diagram as a straight line. For example, if compositions *V* and *G* are mixed in appropriate proportions, the resulting mixture would fall on the line *V G*. If compositions *V* and *L* are mixed, the resulting overall composition *M* would fall on the line *V L* but the mixture would yield two phases. If two phases are formed, their compositions, *V*1 and *L*1, would be given by a tie line extended through the point *M* to the phase envelope. The part of the phase boundary on the phase envelope from the critical point *C* to point V_0 is the dew point curve. The phase boundary from *C* to L_0 is the bubble point curve. The entire bubble point–dew point curve is referred to as the binodal curve.

The oil–LPG–dry gas system will be used to illustrate the behavior of the first-contact miscible process on a ternary diagram. Figure 3 is a ternary diagram with the points *O*, *P*, and *V* representing the oil, LPG, and dry gas, respectively. The oil and LPG are miscible in all proportions. A mixing zone at the oil–LPG interface will grow as the front advances through the reservoir. At the rear of the LPG slug, the dry gas and LPG are miscible and a mixing zone will also be created at this interface. If the dry gas–LPG mixing zone overtakes the LPG–oil mixing zone, miscibility will be maintained unless the contact of the two zones yields mixtures inside the two-phase region (see line $M_0 M_1$, Figure3) .
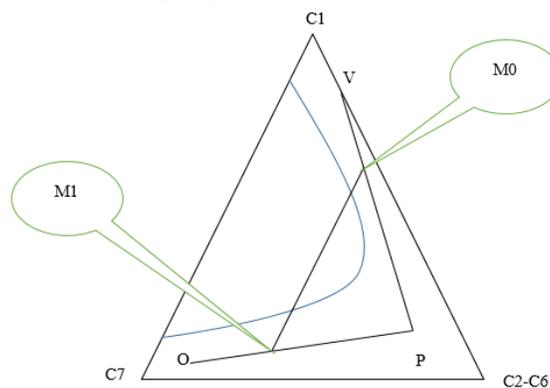

Figure 3 : Ternary diagram illustrating the single-contact miscible process

Reservoir pressures sufficient to achieve miscibility are required. This limits the application of LPG processes to reservoirs having pressures at least of the order of 1500 psia. Reservoirs with pressures less than this might be amenable to alcohol flooding, another first-contact miscible process, since alcohols tend to be soluble with both oil and water (the drive fluid in this case). The two main problems with alcohols are that they are expensive and they become diluted with connate water during a flooding process, which reduces the miscibility with the oil. Alcohols that have been considered are in the C1–C4 range.

Multiple Contact Miscible Process

Multiple-contact, or dynamic, miscible processes do not require the oil and displacing fluid to be miscible immediately on contact but rely on chemical exchange between the two phases for miscibility to be achieved. Figure 4 illustrates the high-pressure (lean-gas) vaporizing process. The temperature and pressure are constant throughout the diagram at reservoir conditions. A vapor denoted by *V in* figure 4 consisting mainly of methane and a small percentage of intermediates, will serve as the injection fluid. The oil composition is given by the point *O*. The following sequence of steps occurs in the development of miscibility:
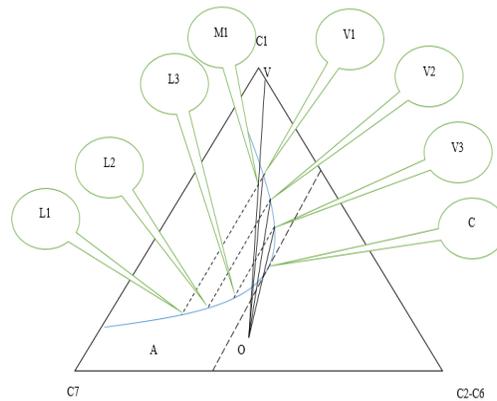

Figure 4: Ternary diagram illustrating the multi contact dry gas miscible process

1.The injection fluid *V* comes in contact with crude oil *O*. They mix, and the resulting overall composition is given by *M*1. Since *M*1 is located in the two-phase region, a liquid phase *L*1 and a vapor phase *V*1 will form with the compositions given by the intersections of a tie line through *M*1 with the bubble point and dew point curves, respectively.

2.The liquid *L*1 has been created from the original oil *O* by vaporization of some of the light components. Since the oil *O* was at its residual saturation and was immobile due to *K*ro's being zero, when a portion of the oil is extracted, the volume, and hence the saturation, will decrease and the oil will remain immobile. The vapor phase, since *K*rg is greater than zero, will move away from the oil and be displaced downstream.

3.The vapor *V*1 will come in contact with fresh crude oil *O*, and again the mixing process will occur. The overall composition will yield two phases, *V*2 and *L*2. The liquid again remains immobile and the vapor moves downstream, where it comes in contact with more fresh crude.

4.The process is repeated with the vapor phase composition moving along the dew point curve, *V*1–*V*2–*V*3, and so on, until the critical point, *c*, is reached. At this point, the process becomes miscible. In the real case, because of reservoir and fluid property heterogeneities and dispersion, there may be a breaking down and a reestablishment of miscibility. Behind the miscible front, the vapor phase composition continually changes along the dew point curve. This leads to partial condensing of the vapor phase with the resulting condensate being immobile, but the amount of liquid formed will be quite small. The liquid phase, behind the miscible front, continually changes in composition along the bubble point. When all the extractable components have been removed from the liquid, a small amount of liquid will be left, which will also remain immobile. There will be these two quantities of liquid that will remain immobile and will not be recovered by the miscible process. In practice, operators have reported that the vapor front travels 20 to 40ft from the wellbore miscibility is achieved. The high-pressure vaporizing process requires a crude oil with significant percentages of intermediate compounds. It is these intermediates that are vaporized and added to the injection fluid to form a vapor that will eventually be miscible with the crude oil. This requirement of intermediates means that the oil composition must lie to the right of a tie line extended through the critical point on the binodal curve (Fig.4). A composition lying to the left, such as denoted by point *A*, will not contain sufficient intermediates for miscibility to develop. This is due to the fact that the richest vapor in intermediates that can be formed will be on a tie line extended through point *A* . Clearly, this vapor will not be miscible with crude oil *A* . As pressure is reduced, the two-phase region increases. It is desirable, of course, to keep the two-phase region minimal in size. As a rule, pressures of the order of 3000 psia or greater and an oil with an American Petroleum Institute (API) gravity greater than 35 are required for miscibility in the high-pressure vaporizing process.The enriched-gas-condensing process is a second type of dynamic miscible process (Fig.5) . As in the high pressure vaporizing process, where chemical exchange of intermediates is required for miscibility, miscibility is developed during a process of exchange of intermediates with the injection fluid and the residual oil. In this case , however, the intermediates are condensed from the injection fluid to yield a "new" oil, which becomes miscible with the "old" oil and the injected fluid. The following steps occur in the process:

1. An injection fluid G rich in intermediates mixes with residual oil O .
2. The mixture, given by the overall composition M1 separates into a vapor phase V1 and a liquid phase L1.
3. The vapor moves ahead of the liquid that remains immobile. The remaining liquid L1 then comes in contact with fresh injection fluid G. Another equilibrium occurs, and phases having compositions V2 and L2 are formed.
4. The process is repeated until a liquid is formed from one of the equilibration steps that is miscible with G. Miscibility is then said to have been achieved.

Figure 5: Ternary diagram illustrating the multi contact enriched gas-condensing miscible process

Ahead of the miscible front, the oil continually changes in composition along the bubble point curve. In contrast with the high-pressure vaporizing process, there is the potential for no residual oil to be left behind in the reservoir as long as there is a sufficient amount of G injected to supply the condensing intermediates. The enriched gas process may be applied to reservoirs containing crude oils with only small quantities of intermediates. Reservoir pressures are usually in the range 2000–3000 psia. The intermediates are expensive, so usually a dry gas is injected after a sufficient slug of enriched gas has been injected.

Gas Oil Relative Permeabilities in Miscible Regions

$$K_{roil} = \frac{S_{oil}}{S_n} K_{rn}(S_n) \tag{1}$$

$$K_{rsg} = \frac{S_{Solvent} + S_{gas}}{S_n} K_{rn}(S_n) \tag{2}$$

Where
K_{rsg}： is the total relative permeability of the gas and solvent .
$$S_n = S_{gas} + S_{solvent} + S_{oil} \tag{3}$$
$K_{rn}(S_n)$： is the relative permeability of hydrocarbon to water .

Transition between Miscible and Immiscible Regimes
In practice there will be regions of transition where the displacement is changing from miscible to immiscible in character. Typically this occurs when a lean chase gas breaks through the solvent slug. Todd and Longstaff recommend that the displacement will be miscible until the solvent saturation becomes very small (of the order of 0.01). However, this transition is likely vary from case to case.
The transition algorithm has two steps:
    1.   Scale the relative permeability end points by the miscibility function. For example, the residual oil saturation is :

$$S_{or} = S_{orm}M + S_{ori}(1 - M) \tag{4}$$

Where
S_{orm}： is the miscible residual oil saturation .
S_{ori}： is the immiscible residual oil saturation .
M： is the miscibility function .
Similarly, for the solvent gas

$$S_{Sgr} = S_{sgrm}M + S_{sgri}(1 - M) \tag{5}$$

Where
S_{sgrm}： is the miscible residual solvent + gas saturation .
S_{sgri}： is the immiscible residual solvent + gas saturation .

2.   Calculate the miscible and immiscible relative permeabilities, scaling for the new end points. Then the relative permeability is again an interpolation between the two using the miscibility function :

$$K_r = K_{rm}M + K_{ri}(1 - M) \tag{6}$$

    Where

K_{rm} : is the scaled miscibility K_r .
K_{ri} : is the scaled immiscible K_r .

Effect of Water Saturation in Miscible Regions

A feature of miscible gas injection processes that may also be modeled is the screening effect of high water saturation on the contact between the miscible gas and the in-place oil in each grid cell. The effective residual oil saturation to a miscible gas drive is found to increase with increasing water saturation, and correct modeling of the effect is important since it may reduce the efficiency of the miscible displacement. The process is modeled by introducing an effective residual oil saturation, S_{or} , which depends on the water saturation $\left(S_{or} = S_{or}(S_w) \right)$.

A mobile oil saturation is then calculated by

$$S_o^* = MAX(S_o - S_{or}, 0.0) \tag{7}$$

For completeness, a corresponding mobile gas saturation has been defined in which a critical gas saturation $\left(S_{gc} = S_{gc}(S_w) \right)$ is specified for the miscible flood .

$$S_g^* = MAX(S_g - S_{gc}, 0.0) \tag{8}$$

The mobile oil and gas saturations S_o^* , S_g^* are then used to determine the miscible component relative permeabilities and the effective viscosities and densities in each grid cell.

3D View of Simulated Reservoir
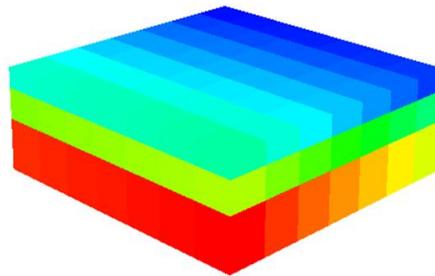
Figure 6 : 3D view of simulated reservoir

In this simulation investigated some parameters such as :
- Effect of Reservoir Pressure on Miscible Flooding .
- Effect of Miscible Gas Density at Surface Conditions on Miscible Flooding .
- Effect of Oil Density at Surface Condition on Miscible Flooding .
- Effect of Initial Water Saturation on Miscible Flooding .
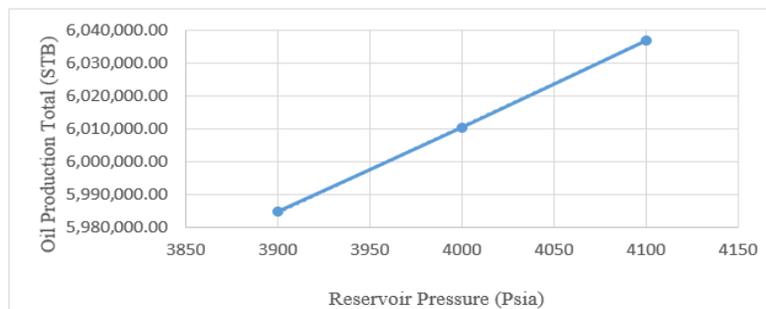- Effect of Gas Density at Surface Condition on Miscible Flooding .

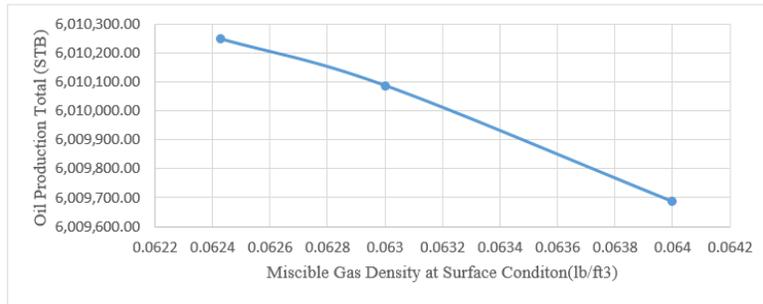**Figure 7 :** Effect of Reservoir Pressure on Miscible Flooding

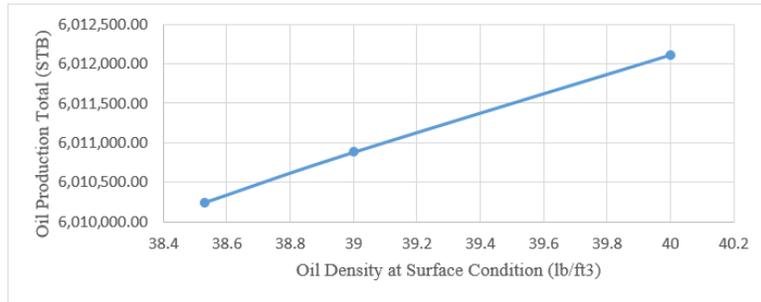**Figure 8 :** Effect of Miscible Gas Density at Surface Conditions on Miscible Flooding

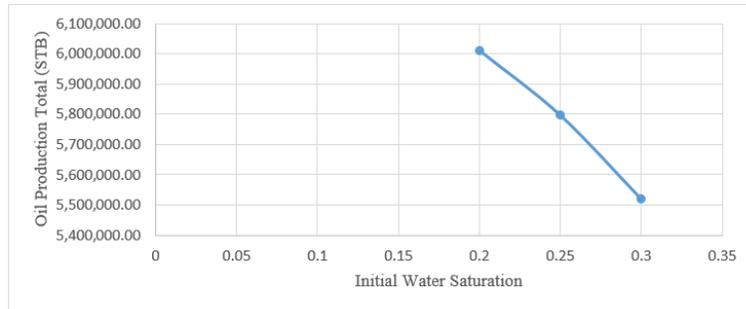**Figure 9 :** Effect of Oil Density at Surface Condition on Miscible Flooding

Figure 10 : Effect of Initial Water Saturation on Miscible Flooding
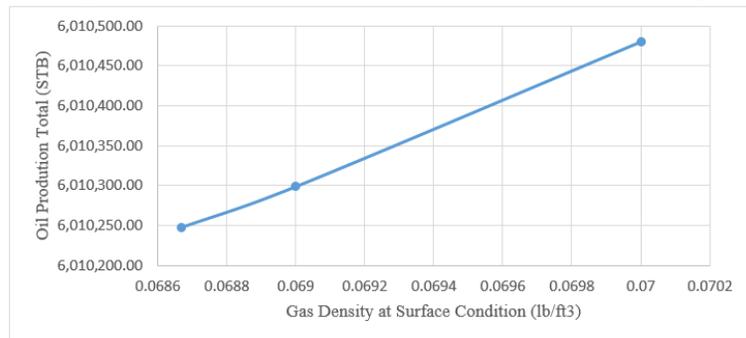

Figure 11 : Effect of Gas Density at Surface Condition on Miscible Flooding

Conclusion

The injection gas and the reservoir oil should form a single phase fluid when mixed at any ratio in this process. This can happen either with very rich injection gases, or at very high pressures. The injection of such a highly rich gas to displace oil is not normally economical. It is also often beneficial to deplete a high pressure under saturated oil reservoir, and displace oil miscibility by vaporizing gas drive at lower pressures than by first contact miscible displacement at high pressures, because high pressure gas injection is also usually a very expensive operation. Intermediate hydrocarbons, such as propane, butane and liquefied petroleum gases (LPG), known as solvents, are usually first-contact miscible with oil at typical reservoir conditions. As the solvents are expensive, they are generally injected as a slug, driven by a lean gas such as methane or nitrogen. The lean gas and the solvent slug should also be miscible for an efficient displacement. Methane (lean gas), or nitrogen can displace oil very efficiently by developing a miscible bank through vaporizing the oil intermediates. The minimum miscibility pressure for methane or nitrogen has been studied by several investigators. Firoozabadi and Aziz (1986) used experimental slim tube data, and proposed a correlation to estimate MMP for vaporizing gas drive processes, though it was considered more reliable for methane than nitrogen injection.

$$P_m = 65.04 - 1.296 \times 10^5 X_{C_2-C_5}/(M_{C_{7+}}(1.8T - 460)^{0.25})$$
$$+1430 \times 10^5 [X_{C_2-C_5}/(M_{C_{7+}}(1.8T - 460)^{0.25})]^2 \tag{9}$$

Where

P_m: Minimum miscibility pressure , MPa .

$X_{C_2-C_5}$: Mole fraction of intermediate in oil , ethane to pentane inclusive .

$M_{C_{7+}}$: Molecular weight of heptane plus .

T : Temperature , K .

There are some problems in applying the miscible process because of differences in density and viscosity between the injected fluid and the reservoir fluid(s), the miscible process often suffers from poor mobility. Viscous fingering and gravity override frequently occur. The simultaneous injection of a miscible agent and a brine was suggested in order to take advantage of the high microscopic displacement efficiency of the miscible process and the high macroscopic displacement efficiency of a waterflood. The improvement was not as good as hoped for since the miscible agent and brine tended to separate due to density differences, with the miscible agent flowing along the top of the porous medium and the brine along the bottom.

Several variations of the simultaneous injection scheme have been suggested and researched. They typically involve the injection of a miscible agent followed by brine or the alternating of miscible agent–brine injection. The latter variation has been named the WAG (water alternate gas) process and has become the most popular(Figure 7). A balance between amounts of injected water and gas must be achieved.
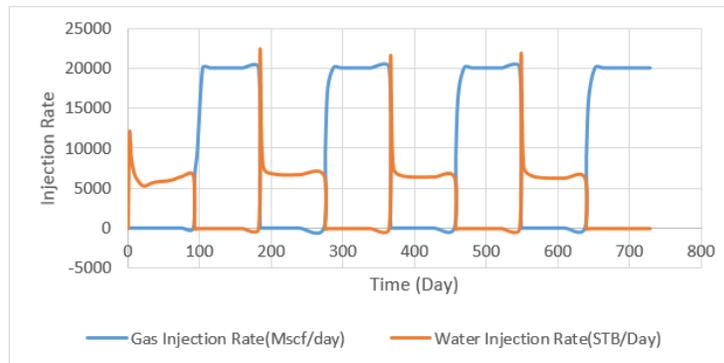

Figure 12 : Water alternate gas injection in miscible flooding (Simulated Model)

Too much gas will lead to viscous fingering and gravity override of the gas, whereas too much water could lead to the trapping of reservoir oil by the water. The addition of foam-generating substances to the brine phase has been suggested as a way to aid in reducing the mobility of the gas phase. Research is continuing in this area.

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