Miscibility and Miscible Displacement

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Summary. Miscible displacement has been developed as a successful EOR process in the past 25 years. Two types of miscible displacement exist: first-contact and multicontact miscible displacement. An understanding of the definition of miscibility and how injected fluids react with reservoir fluids is necessary to understand these processes.

Miscibility

Through research over the past 25 years, miscible-phase displacement processes that use certain gases as injectants have been developed as successful means for increasing oil recovery from many reservoirs. To understand these processes it is first necessary to provide a definition of "miscibility," particularly as distinguished from "solubility." Solubility is defined as the ability of a limited amount of one substance to mix with another substance to form a single homogeneous phase. Miscibility is defined as the ability of two or more substances to form a single homogeneous phase when mixed in all proportions.

For petroleum reservoirs, miscibility is defined as that physical condition between two or more fluids that will permit them to mix in all proportions without the existence of an interface. If two fluid phases form after some amount of one fluid is added to others, the fluids are considered immiscible. An interfacial tension (IFT) exists between the phases when they are immiscible. When a substantial IFT (>0.1 dynes/cm) exists between phases in a porous medium, capillary forces prevent the complete displacement of one of those phases by the other. A substantial residual oil saturation remains in a porous medium after an injected immiscible fluid is used to displace oil from the medium, as in waterflooding. Figs. 1 and 2 illustrate the differences between immiscible and miscible conditions for certain fluids.

Miscible Displacement

Miscible displacement implies that with the IFT between the oil and displacing fluid eliminated (IFT=0), the residual oil saturation will be reduced to zero in the swept region. There are basically two types of miscible displacements: first contact and multicontact. The term first contact means that any amount of the solvent can be injected and will exist as a single phase with the oil in the reservoir. Low-molecular-weight hydrocarbons—such as propane, butane, or mixtures of liquefiable petroleum gas (LPG)—or heavier hydrocarbons—such as gasoline fractions—have been used as solvent for first-contact miscible flooding.

In practice, solvents for first-contact miscibility are usually too expensive for continuous injection. Instead, attempts have been made to inject a limited solvent volume, or slug, which conceptually can be miscibly displaced with a less expensive fluid, such as methane, nitrogen, or flue gas. This chase fluid, in turn, is immiscibly displaced by water, leaving a residual saturation of the chase fluid.

Multicontact or dynamic miscible displacements are of two mechanistic types: vaporizing-gas drive and condensing-gas drive. In the vaporizing-gas-drive process, a lean gas (i.e., methane, nitrogen, or flue gas) is injected, and as it travels through the reservoir, it vaporizes methane through LPG components from the reservoir oil. When the leading edge of the displacing gas front has vaporized sufficient hydrocarbons, it becomes miscible with virgin reservoir fluid. A similar mechanism occurs when CO_2 is injected as a liquid or critical fluid. However, highly compressed CO_2 extracts heavier (gasoline-range) hydrocarbons from the reservoir oil, which allows the displacement front to become miscible at lower pressures than those required for the lean gas.

In the condensing-gas-drive process, an enriched gas (containing hydrocarbons heavier than methane) is injected, and as it travels through the reservoir, it gives up heavier components to the oil. When the oil becomes sufficiently enriched, it becomes miscible with freshly injected enriched gas. Both types of multicontact miscible displacements require a transfer of hydrocarbon components between the injected and the reservoir fluid under dynamic conditions.

Measurement of Miscible Fluid Conditions

Miscibility between the reservoir oil, solvent, and gas is a function of the composition of these fluids and the pressure and temperature in the reservoir during the displacement process. At a given reservoir temperature, the pressure required to achieve miscible displacement can be estimated from published correlations.

First-contact miscibility can be determined experimentally with a high-pressure visual cell. The reservoir oil and solvent are combined in the cell at reservoir temperature. First-contact miscibility is achieved at the pressure when the interface between the fluids disappears.

The most common method used to determine the conditions at which multicontact miscible displace-

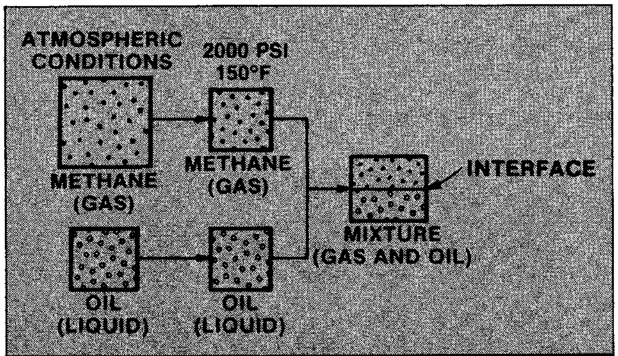

Fig. 1—Immiscibility of methane (gas) and oil (liquid) at reservoir conditions of temperature and pressure.

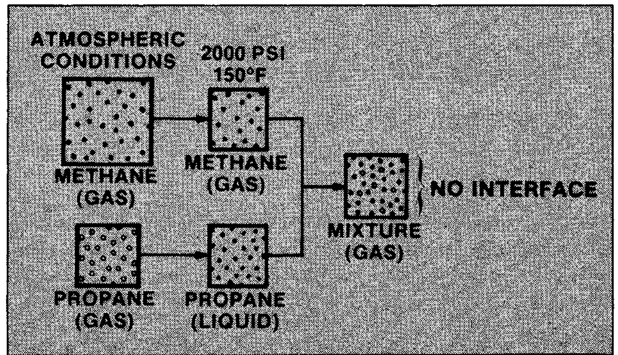

Fig. 2A—Miscibility of methane (gas) and propane (or LPG) liquid at reservoir conditions of temperature and pressure. Here propane (or LPG) is a gas in the presence of a gas.

ment is achieved is known as "slim-tube displacement." A long (40- to 80-ft [12- to 24-m]), small-diameter (¼-in. [0.6-cm] -ID), high-pressure tube is packed with clean sand (or glass beads) to achieve a fluid permeability of about 3 to 5 darcies. This sandpack is then saturated with the reservoir oil of interest, and the apparatus is maintained at reservoir temperature. A series of floods is conducted at different pressures, while the displacement fluid (gas or liquid) of interest is injected. An oil-recovery curve vs. pressure is developed as shown in Fig. 3. Miscible displacement is achieved at the flooding pressure where about 95% of the oil in the tube is recovered after about 1.3 PV's of fluid has been injected. Note that below this minimum miscibility pressure, oil recovery decreases sharply. This is typical for displacement at low temperatures (less than about 150°F [66°C]). A more gradual change in oil recovery occurs at higher temperatures. Visual observation of the appearance of the fluids produced from the tube near the completion of the flood is helpful in pinpointing the conditions of miscibility.

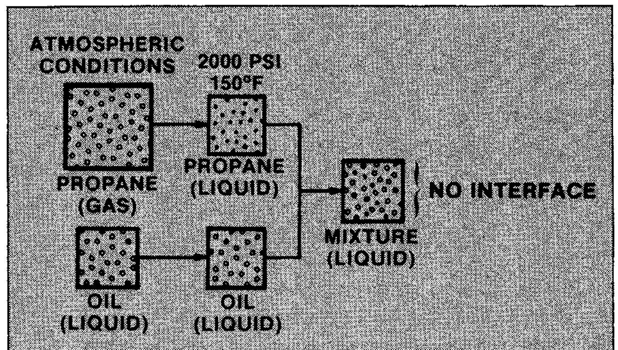

Fig. 2B—Miscibility of propane (or LPG) liquid and oil liquid at reservoir conditions of temperature and pressure. Here propane (or LPG) liquid is a liquid in the presence of a liquid.

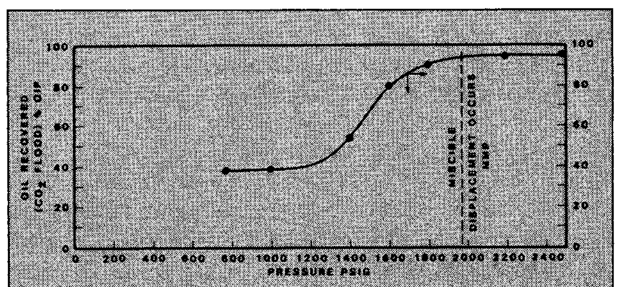

Fig. 3—Recovery of oil from 48-ft-long sandpack by CO_2 flooding at various pressures (at 135°F).

SI Metric Conversion Factors

ft	× 3.048*	E−01	= m
°F	(°F−32)/1.8		= °C
lbf	× 4.448 222	E+00	= N
psi	× 6.894 757	E+00	= kPa

*Conversion factor is exact.

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