PERMIAN BASIN: HISTORICAL REVIEW OF CO_2 EOR PROCESSES, CURRENT CHALLENGES AND IMPROVED OPTIMIZATION POSSIBILITIES

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ABSRACT
The use of CO_2 as an Enhanced Oil Recovery (EOR) fluid in miscible displacement processes was pioneered in the Permian Basin of West Texas and New Mexico. In this paper we conducted a comprehensive review of the process by looking at the technological and scientific innovations and improvements made over the years. The paper enumerates the current and attendant challenges and proposes some ideas by which the process can be further optimized. The Permian Basin CO_2 miscible injection projects are a reference mark for the industry. However, the success story has been mixed and definite scientific procedures or guidelines and generalized procedure for optimization of the process are still lacking. The intricate dynamics and predictability of this miscible recovery process is not fully understood. A review of the literature and field reports shows that the implementation of the process is field-specific and there is really no standardized procedure for executing a successful project. This paper raises some fundamental questions which call for further investigations and research into how this process can be further optimized to increase hydrocarbon recovery in the CO_2 miscible process. Microscopic displacement in porous media is influenced by viscous, gravity, capillary and dispersion forces. However, for the CO_2 miscible displacement, the phase behavior of the fluids which is a direct function of the pressure, temperature and composition of the reservoir fluids is of prime importance. Therefore, a global and rigorous approach to optimization is the integration of all these important variables in the optimization function. Literature review and field reports show that most projects are implemented after running several numerical reservoir simulation scenarios, which themselves are limited principally by CO_2 availability and process economics. The minimum miscibility pressure (MMP) plays a very important role and it is one of the primary parameters evaluated before a project can be initiated. This paper looks at how MMP is currently measured or calculated and suggests more practically representative ways by which MMP can be measured, so that its value will be consistent and representative of expected field performance. Practical suggestions are also made on how the MMP can be lowered, thus making some previously overlooked reservoirs amenable for CO_2 miscible injection.

INTRODUCTION
The production of hydrocarbon from reservoirs requires some form of energy. Hydrocarbon production has been classified into primary and augmented (secondary and tertiary) recovery. Primary recovery, which uses the innate energy of the reservoir, its fluids and the adjoining aquifer to produce the hydrocarbons, has been grouped mainly into gas cap drive, solution gas drive, water drive and combination drive.

Secondary recovery which is predominantly pressure maintenance is grouped into water flooding and gas injection. The tertiary recovery, also called enhanced oil recovery (EOR) is divided principally into thermal, chemical, microbial and miscible gas injection. The main target of this paper is miscible gas injection which involves the injection of a gas that is miscible with the reservoir oil under reservoir conditions of pressure and temperature.

The development of miscibility between the injected gas and the reservoir oil is essential to the recovery process. Miscibility can either be first contact miscibility (FCM), or multiple contact miscibility (MCM), also called dynamic miscibility. The pressure at which miscibility between the injected fluid and the reservoir oil can be achieved is called the minimum miscibility pressure (MMP), which has become an important screening criteria for reservoirs selected for this process. Miscible gas injection is also characterized by the type of gas injected, and as of today, several gases have been injected in hydrocarbon reservoirs as part of EOR processes. These include nitrogen, flue gas, air, hydrocarbon gases and carbon dioxide (CO_2). However, of all these gases, CO_2 is the most economically viable and its use in field wide applications has been confirmed through several projects worldwide.

PERMIAN BASIN

The Permian Basin is located in West Texas and the neighboring area of southeastern New Mexico. It comprises of the Midland Basin, the Central Basin Platform and the Delaware Basin. It underlies an area approximately 402 km wide and 482 km long, or about 194,166 sq. km. The greatest thickness of sediments in the Basin was deposited in the Paleozoic era. The deposits in the Basin are the thickest deposits of Permian rocks found anywhere in the world [6].

Most Permian Basin oil reservoirs have been depleted through primary and secondary phases and most are at the tertiary stage of their productive life. The predominant secondary recovery mechanism is water flooding. The combined recovery from primary and water flooding operation basin-wise is about 20-40%. The high residual oil in place (ROIP) opens up a huge opportunity for implementation of EOR processes.

The EOR technique that is widely used in the Permian Basin is the CO_2-EOR, it can be said that the Permian Basin is the pioneer and reference point for CO_2-EOR globally. The huge success of this process in the Basin is due principally to the following reasons:

- Availability of low priced CO_2
- Favorable oil composition
- Huge ROIP yet to be recovered
- Proven and constantly improving CO_2 EOR technology

Especially noteworthy is the discovery of natural CO_2 reservoirs in the Sheep Mountain and the McElmo dome, both in Colorado and Bravo dome in New Mexico. The CO_2 gas is transported to the Permian Basin fields via pipeline networks operated by CO_2 companies in and outside of the Basin. This has greatly reduced the price of CO_2 used for the injection process.

CO_2 MISCIBLE FLOOD

CO_2 injection is currently the most economical miscible EOR method. Additionally, CO_2 can be sequestered in the reservoirs after oil recovery, which is good for the environment. CO_2 flooding mobilizes the residual oil left behind after water-flooding or secondary recovery. The highest recovery occurs when miscibility develops between CO_2 and reservoir oil, this underscores the importance of the MMP. The MMP is a parameter that must be determined before a project can be initiated. The MMP can be calculated using the following methods (Elsharkawy et al., (1996)):

- Experimental Methods: slim tube, rising bubble (RB), vanishing interfacial tension (VIT), pressure-composition (P-X) diagram, etc.
- Equation of State (EOS) Methods
- Analytical Methods
- Correlations

The CO_2–EOR process is a multiple contact miscibility process, which implies that CO_2 does not mix with the oil at first contact, but a process of stripping of light components from the oil (vaporization) and condensing of heavier component from the CO_2 mixture subsequently leads to the development of miscibility over time. CO_2 as a gas has a critical pressure (P_c) of 7382 kPa and a critical temperature (T_c) of 304.4 K. It is a supercritical fluid at the conditions for miscibility in the reservoir. The main factors determining miscibility are pressure, composition and temperature. These parameters dictate if miscibility will be achieved for a particular crude oil system. When CO_2 is injected into the reservoir at or above the miscibility pressure, the objective is that dynamic miscibility will develop after multiple contacts in the reservoir. However, due to the lower density and higher viscosity of CO_2 relative to oil, viscous fingering takes place, especially if the reservoir pressure is not adequately maintained above the MMP. This is a major cause of gas cycling which leads to poor utilization of injected CO_2 in the reservoir. To mitigate this scenario, water is injected with the CO_2 in alternating cycles to reduce viscous fingering. Figure 1 adapted from Jarrel et al., (2002) shows the various CO_2 injection schemes being practiced. The choice of which injection scheme to use is usually based on numerical simulation, field experience, and heuristic methods which do not rely on any rigorous scientific criteria or justification. This is one of the "black boxes" of the CO_2-EOR process as practiced today.

SCIENTIFIC AND TECHNOLOGICAL ADVANCES MADE

Huge strides have been made in the development and adaptation of technology for CO_2-EOR processes over the years compared to the earlier days of CO_2 flooding. The advances made were the result of intense research and a need to optimize the process and improve recovery. There are many challenges to the process and a tabulation of challenges versus industry's solutions is given in Table 1, from [NETL, 2006] although this is not an exhaustive listing. There are still some operational problems and challenges being faced by operators, research is equally ongoing to make the process more productive and efficient.

THE NEED FOR PROCESS OPTIMIZATION

The fact that CO_2 recovers residual oil is well known and accepted. However, the process as it is practiced today is not efficient. Most CO_2 based enhanced oil recovery projects are performing below attainable oil recovery based on results from coreflooding experiments or slim tube tests.

An investigation sponsored by the U.S. Department of Energy (DOE) [ARI, 2006] showed that the current “traditional practice” of CO_2-EOR will leave billions of barrels of recoverable oil behind in the Permian Basin. Therefore there is a need for more in-depth research and investigations into how the process can be further optimized on all fronts. This may require a rethinking of the process dynamics and field implementation or a collaborative synergy of industry’s knowledge base on CO_2-EOR. The following reasons were suggested as bottlenecks to the CO_2-EOR process efficiency by Kuuskraa (2008), based on a study of some Permian Basin reservoirs;

- Geologically complex reservoirs
- Limited process control; like reservoir pressures, viscous fingering, gravity override
- Insufficient CO_2 injection

CO_2-EOR is a huge resource potential which is yet to be fully tapped into, we need to invest resources and effort into understanding and harnessing this immense opportunity.

SUGGESTIONS FOR IMPROVEMENT AND RESEARCH ROUTE

This section is aimed at raising some fundamental questions and proposing ways by which the gap between principle or concept and field reality could be bridged. We suggested that a “systems thinking” approach is needed in optimizing the CO_2-EOR process, the component parts should be individually optimized and improved upon to achieve a wholly synergized and optimized process. We have listed some of the issues under topical heads as discussed below;

Minimum Miscibility Pressure (MMP) Measurement: The determination of the MMP from the literature reviewed does not include the effect of the formation water. The models and the laboratory technique used in MMP does not account for the effect of the water saturation on the MMP. Researching the effect of formation water (and its properties) on the calculated MMP and seeing how this changes/affects the dynamics of the process will be a worthwhile venture.

The MMP calculated initially will change as the properties of the reservoir fluid changes with production. An investigation into the dynamics of this change, as the composition of the reservoir fluid changes with production and modeling this scenario will be beneficial.

CO_2 Volume to Inject: A review of the literature has shown that there is no analytical method by which the optimal volume of CO_2 to be injected is determined. There is no scientific basis for field practice and the selection of any injection volume or scheme. Optimal volume prior to the initiation of CO_2 injection should be known, CO_2 injection volumetrics is currently a big “black box”, with a lot of unknowns. There is a need for proper material balance of the injected CO_2; how much will be dissolved in the water, how much will actually mixing with the crude, etc. should be known so that an operator can accurately determine CO_2 utilization during the flood. This will be highly beneficial to the economics of CO_2 floods.

Reservoir Characterization: Adequate characterization of the reservoir is imperative for the success of a CO_2 flood. Operators need to understand the petrology and mineralogy of their reservoirs and know the rock and rock-fluid properties that bear on the success of the flood. CO_2 flood cannot be handled like water flooding; it is a process that requires much more knowledge of the reservoir. This can be done by adequate coring of the constituent units of the reservoir.

Reservoir Management: Reservoir monitoring, surveillance and active flood management is critical, quick response and plans modification to meet operational challenges must be put in place. The reservoir pressure has to be monitored; the success of the process is highly pressure dependent, therefore ensuring adequate reservoir pressure data field-wide is paramount. Excellent communication and pro-activeness should be exhibited by project team members.

Flood Patterns and Well Placement: It is essential that the injected CO_2 contacts the reservoir oil. This can be achieved by monitoring the saturation front, swept areas and positioning wells in locations where they will enhance process optimization. Currently there is no technique used for evaluating the efficiency of the CO_2 flood on a pattern basis.

CONCLUSIONS

CO_2-EOR is a process that has been confirmed to be economically viable especially in the Permian Basin. However, there are lots of challenges being faced by operators, the success story is mixed. There is a need for process optimization, so that full potential can be achieved. The displacement principles and dynamics are still not fully known. The measurement of the MMP should be standardized and its value should be practically representative of the displacement dynamics and scenario in the porous media. More research and investigations are needed to standardize the CO_2-EOR process in general. This will make the lessons learnt over the years in the Permian Basin universally applicable to other Basins.

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Table 1: Some solutions to CO_2-EOR operational problems

Problems/Challenges	Proffered/Applied Technology
Poor sweep efficiency and mobility control issues	• Varieties of water alternate gas (WAG) schemes • CO_2 foams • Chemical gels • Mechanical isolation of zones • Direct thickening agent (CO_2 viscosity modifiers)
Location of residual oil and CO_2 front in the reservoir	• Time-lapse or 4-D seismic monitoring
Flood management	• 3-D reservoir characterization, integration of core data into 3-D seismic • Injection monitoring with cross-well electromagnetic imaging (EM) • Use of horizontal wells to increase CO_2 reservoir contact
Early gas breakthrough (High GOR)	• Zonal injection tracking • Automated field monitoring system
CO_2 supply	• Natural CO_2 reservoirs • Anthropogenic CO_2 • CO_2 capture technology
Corrosion in tubular	• Use of stainless steel • Fiber glass coated tubing
Asphaltenes deposition	• Use of asphaltene inhibitors • Mechanical cleaning • Chemical Cleaning
Injectivity losses	• WAG tapering • Well realignment • Horizontal injection wells
Scales deposition	• Scale inhibitor treatment

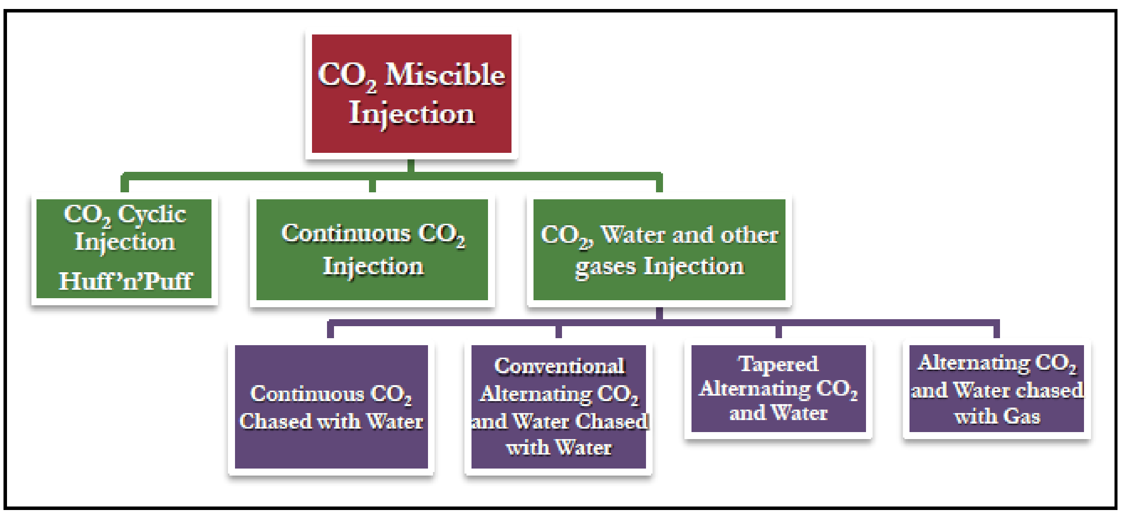

Figure 1: CO_2 miscible gas injection schemes