Summary of the Analyses for Recovery Factors

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Chapter E of
Three Approaches for Estimating Recovery Factors in Carbon Dioxide Enhanced Oil Recovery
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Chapter E. Summary of the Analyses for Recovery Factors

By Mahendra K. Verma[1]

Overview

In order to determine the hydrocarbon potential of oil reservoirs within the U.S. sedimentary basins for which the carbon dioxide enhanced oil recovery (CO_2-EOR) process has been considered suitable, the CO_2 Prophet model was chosen by the U.S. Geological Survey (USGS) to be the primary source for estimating recovery-factor values for individual reservoirs. The choice was made because of the model's reliability and the ease with which it can be used to assess a large number of reservoirs. The other two approaches—the empirical decline curve analysis (DCA) method and a review of published literature on CO_2-EOR projects—were deployed to verify the results of the CO_2 Prophet model. This chapter discusses the results from CO_2 Prophet (chapter B, by Emil D. Attanasi, this report) and compares them with results from decline curve analysis (chapter C, by Hossein Jahediesfanjani) and those reported in the literature for selected reservoirs with adequate data for analyses (chapter D, by Ricardo A. Olea).

To estimate the technically recoverable hydrocarbon potential for oil reservoirs where CO_2-EOR has been applied, two of the three approaches—CO_2 Prophet modeling and DCA—do not include analysis of economic factors, while the third approach—review of published literature—implicitly includes economics. For selected reservoirs, DCA has provided estimates of the technically recoverable hydrocarbon volumes, which, in combination with calculated amounts of original oil in place (OOIP), helped establish incremental CO_2-EOR recovery factors for individual reservoirs.

The review of published technical papers and reports has provided substantial information on recovery factors for 70 CO_2-EOR projects that are either commercially profitable or classified as pilot tests. When comparing the results, it is important to bear in mind the differences and limitations of these three approaches.

Discussion of Recovery Factors with CO_2-EOR from Three Sources

The CO_2 Prophet model was used to evaluate the potential reservoir performance of the CO_2-EOR process using geologic, reservoir, and production data from a comprehensive resource database (CRD) described by Carolus and others (in press). To demonstrate the effectiveness of the model, seven plays containing 143 clastic reservoirs within the Powder River Basin of Wyoming and Montana were chosen to determine recovery-factor (*RF*) values of individual reservoirs as well as to study the sensitivity of some of the reservoir parameters that may have significant effects on *RF* values. The median *RF* values for the seven plays within the Powder River Basin range from 9.50 to 13.43 percent of the OOIP, which seems reasonable when compared to published values adjusted for the amount of CO_2 injected during EOR, expressed as a percentage of the hydrocarbon pore volume (HCPV). The range of calculated *RF* values reflects the variations in reservoir heterogeneity as measured by the pseudo-Dykstra-Parsons coefficient, the oil viscosity, and other variables that may affect the *RF*. For each reservoir, the residual oil saturation (*Sorw*) at the initiation of CO_2-EOR that was preceded by waterflooding was assumed to be 0.25 (which can also be expressed as 25 percent), because all evaluated reservoir lithologies were clastic. Each reservoir was assumed to have a volume of CO_2 equal to 100 percent of the HCPV injected over the duration of the EOR program. However, additional runs were made to assess the impact of increasing the injection volume to 150 percent of the HCPV, and the results showed an increase of 2.5 to 3.5 percentage points in the *RF* values. Also, the incremental increases in the *RF* values due to increased injection are smaller where the value of *Sorw* is smaller.

The DCA evaluation included a total of 15 reservoirs, and the results show that the incremental *RF* values after CO_2-EOR range between 6.6 and 13.8 percent (average 10.9 percent) for the 3 clastic reservoirs and between 7.6 and 25.7 percent (average 13.8 percent) for the 12 carbonate reservoirs, which were mostly dolomites. The results do indicate higher recoveries in carbonate reservoirs compared to clastic reservoirs, but limited data in terms of a smaller number of reservoirs, especially clastic, prevent us from drawing any firm conclusions. Although there were only 15 reservoirs for DCA, their results are found to be within a reasonable range when compared with those from CO_2 Prophet modeling.

A review of technical papers and reports included 70 EOR projects located around the world, of both field-wide application and pilot tests, with the majority of them in the United States. The available information indicates that at CO_2

[1]U.S. Geological Survey.

injection volumes equivalent to 90 percent of the HCPV, the *RF* value for EOR was about 16 percent of the OOIP in carbonate reservoirs and 11.5 percent in clastic reservoirs. This *RF* value for clastic reservoirs (11.5 percent) is falling in the middle of the range of *RF* values from modeling (9.50–13.43 percent) where each reservoir was assumed to have a CO_2 injection volume equivalent to 100 percent of the HCPV.

Discussion of Some Important Variables That Have Significant Effects on *RF* Values

The review of technical papers revealed some interesting observations: (1) all other factors being the same, the larger the value of *Sorw* (oil saturation after waterflooding and prior to application of CO_2-EOR), the higher the *RF* value and (2) one of the attributes of critical importance in reservoir modeling is the *Sorw* in those portions of the reservoir thoroughly flushed by the waterflooding. Unfortunately, reported values of *Sorw* are few despite its importance in CO_2-EOR modeling. The mean values follow closely the default values of 25 percent for clastic reservoirs and 38 percent for carbonate reservoirs used by the National Petroleum Council (NPC, 1984), which later revised the value for carbonate reservoirs to 30.5 percent (Donald J. Remson, National Energy Technology Laboratory, written commun., 2015). The mean values are within the interval of 20 to 35 percent postulated by Tzimas and others (2005). However, neither the numbers from the NPC (1984) nor those from Tzimas and others (2005) are supported by data or references. In the present modeling, the *Sorw* value for clastic reservoirs was set at 25 percent (NPC, 1984), and the value for carbonate reservoirs was set at 30.5 percent (Donald J. Remson, National Energy Technology Laboratory, written commun., 2015). The reservoir information in the CRD could be used by the USGS in an assessment of hydrocarbon potential in the oil reservoirs within the United States that qualify for the application of CO_2-EOR.

Another variable of great importance in *RF* values from the CO_2-EOR modeling is the Dykstra-Parsons coefficient of vertical permeability variation (V_{DP}), as discussed by Tiab and Donaldson (2012). Unfortunately, the information available in the literature is minimal. Because of the lack of data, the algorithm developed by Hirasaki and others (1984, 1989) was used to compute the pseudo-Dykstra-Parsons coefficient. Their algorithm for computing the pseudo-Dykstra-Parsons coefficients resulted in a range in values between 0.5 and 0.98. Due to limitations of the CO_2 Prophet software, the maximum effective value of the pseudo-Dykstra-Parsons coefficient was 0.86 (J.K. Dobitz, Windy Cove Energy, written commun., 2015), and, therefore, the calculated values resulting from the algorithms of Hirasaki and others (1989) that exceeded 0.86 were set to 0.86.

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