

Development of a Correlation Between Performance of CO₂ Flooding and the Past Performance of Waterflooding in Weyburn Oil Field

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Summary

Weyburn oil field, located in southeast Saskatchewan, has been the site of one of the largest carbon dioxide (CO₂) flooding projects in the world since September 2000.

In this paper, data of the past performance of waterflooding in the Weyburn field was used to develop empirical correlations to predict the performance of CO₂ flooding. Two different correlations were developed based on CO₂-injection schemes in Weyburn. The first correlation is based on a water-alternating-gas (WAG) process through vertical wells, and the second correlation is based on the cases in which CO₂ is injected through horizontal wells and water is injected separately through vertical wells. The first step was to collect and analyze production data from 1958 to 2004. Oil-production rates for both waterflooding and CO₂ flooding periods, water-injection rates, and CO₂-injection rates were used in developing the correlations. The empirical model for injecting CO₂ and water through vertical wells was verified using the Kinder Morgan CO₂ flood-scoping model (this is not a trademark product) and actual field production data. The comparative analysis showed 12% error between our simple correlation and the Kinder Morgan model. For injecting CO₂ in horizontal wells, the correlation could not be verified against the Kinder Morgan model, but the correlation followed the actual oil production in the field very closely.

This new model can be used effectively as a screening tool for predicting the performance of CO₂ flooding in various locations in the Weyburn reservoir based on the data obtained from past waterflooding performance and the rate of CO₂ injection. Therefore, it can contribute significant savings in time and expense to the operating oil company. Also, this approach can be used for other potential CO₂-flooding processes in reservoirs with histories and properties similar to those of the Weyburn field.

Introduction

The Weyburn oil field was developed in 1954 while undergoing primary production of medium oil with a American Petroleum Institute (API) degree ranging from 25 to 34 (Fig. 1). Waterflooding started in 1964, and reached its peak production of 7 500 m³/d (47,175 STB/D) in 1966. To maintain production, drilling of vertical infill wells followed by horizontal drilling began in 1986. Initial investigations indicated that CO₂ flooding might be a viable option for enhancing oil recovery from this field. Therefore, CO₂ flooding was commenced in the Weyburn field in September 2000. It is estimated that implementation of a CO₂ flood would extend the economic life of this field more than 25 years, with an incremental recovery prediction of 13 to 19%.

The field has two carbonate layers that are CO₂-flooded: the marly dolomite (upper) and the vuggy limestone (lower). Relative

to the vuggy zone, the marly zone has a tighter formation with an average porosity of 26% and an average permeability of 10 md. The Marly zone has low flow capacity and sweep efficiency. The vuggy zone has an average porosity of 15% and an average permeability of 30 md.

Natural vertical fractures are present in the Weyburn-Midale formations. Three major fracture trends exist in the northeast-southwest, northwest/southeast, and north/south directions. Analysis of logs indicates that the dominant fracture orientation is parallel to the current southwest/northeast orientation (Monea and Wilson 2004).

CO₂ Displacement Process

CO₂ is not first-contact miscible with reservoir oils at most reservoir pressures. However, if the reservoir pressure is at or beyond the minimum miscibility pressure (MMP) of the injected stream of CO₂, multiple-contact miscibility will be achieved in the reservoir. In general, for a given injection-gas composition there is a MMP above which dynamic miscibility can be accomplished. The ability to achieve dynamic miscibility at attainable pressures in a wide range of reservoirs is a major advantage of the CO₂ miscible process. A simplified diagram of the CO₂-injection process is shown in Fig 2.

The advantages of a CO₂-flood include (Stalkup 1983) the following:

- Miscibility can be achieved at relatively low pressures.
- Displacement efficiency is high in miscible cases.
- Recovery of oil is aided by using a solution-gas drive.
- Useful over a wider range of crude oils than hydrocarbon injection methods.
- Miscibility can be regenerated if lost.

The disadvantages of a CO₂ flood may include the following:

- CO₂ is expensive to transport and not always available.
 - Poor sweep and gravity segregation can happen under certain conditions.
 - The risk of corrosion is increased.
 - Special handling and recycling of produced gas is necessary.
- A wide range of initial screening investigations indicated that the Weyburn field is a suitable candidate for CO₂ flooding because:
- The reservoir is continuous.
 - The crude oil swells with CO₂ and has a large viscosity-reduction factor.
 - The horizontal wells create a reduced spacing that makes the CO₂ process very efficient.
 - MMP can be achieved.
 - There has been a successful waterflood that provides good control over the reservoir.

Kinder Morgan CO₂ Flood-Scoping Model

In order to evaluate the outcome of the simplified models developed in this paper, it was decided to compare the results of our models with the Kinder Morgan CO₂ flood-scoping model, where possible. In the petroleum industry, the Kinder Morgan model is considered an industry standard for the CO₂ flood-scoping process. Because of that, the Kinder Morgan tool was used to verify the results of the empirical correlations developed in this study. The Kinder Morgan model was initially created by Shell Oil Co., then



Fig. 1—Location of the Weyburn field.

updated by Kinder Morgan, and is based upon dimensionless curves from the Denver Unit in the San Andres Formation in west Texas (Jarrell 2002). The Kinder Morgan CO₂ model takes advantage of various types of available data for the reservoir to obtain a first-pass estimate of the profitability of a CO₂ flood. This data may include:

- Logs.
- Core samples.
- Maps.
- Production data.
- Well completion history.
- Waterflood-injection history.
- Any other data that may be available.

Developing New Correlations

The main objectives of this work are to develop easy-to-use correlations that are capable of easily predicting the response of an area to CO₂ flooding and to use this information to decide which areas will be the best candidates for this process. If the correlations are proved valid, they can also be used to decide between processes such as WAG injection or horizontal CO₂ injection. To keep the predictions simple, data from completed CO₂ floods was analyzed and correlations between pre-CO₂ flood data and post-CO₂ flood data were developed. Parameters such as response to the previous waterflood, amount of water injected compared to amount of oil produced, pre-CO₂ flood production, and response to CO₂ flooding were used. Because only 4 years of post-CO₂ flood data was available, these correlations extend only 4 years past the implementation of CO₂ flooding and measure only the initial 4-year response to the process.

Two CO₂-injection configurations in the Encana-Weyburn CO₂ project were analyzed. Both configurations use existing nine-spot water injection patterns. The first is a WAG process. The second process is horizontal CO₂ injectors coupled with dedicated water injectors. WAG can be implemented in both horizontal and vertical injectors, and constant CO₂ flooding also occurs in both horizontal and vertical injection wells. In this paper, WAG injection refers to vertical injection wells injecting both water and CO₂, while horizontal injection refers to constant CO₂ injection in horizontal wells. When implementing the horizontal pattern configuration, one two-legged CO₂ injector is drilled around the water injector. Only CO₂ is injected through the horizontal well, while the vertical water injector continues to inject water to reduce the mobility of the CO₂. In both configurations, horizontal producing wells were infill drilled to increase the production of the patterns.

New Correlations for WAG Process

The WAG-injection pattern uses an existing 9-spot water-injection pattern. Two production wells in the middle of the pattern are converted to WAG injectors, and the water-injection well in the middle is also used as a WAG injector. The WAG-injection wells penetrate both the marly and vuggy formations and inject CO₂ and water into both zones.

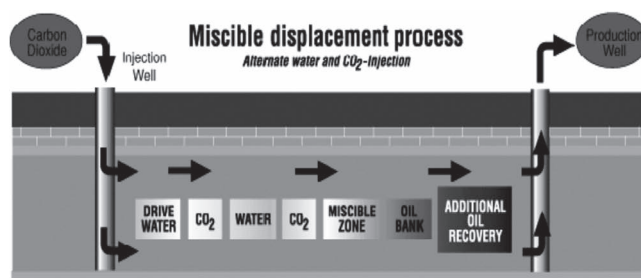


Fig. 2—Miscible CO₂ flood (Stalkup 1983).

Correlations were developed by analyzing production and injection data for the patterns studied. Eight WAG-injection patterns were studied. Various comparisons between waterflood and CO₂-flood responses were made, and some trends emerged between the variables studied. Data is in the form of a 4-year average where pre-CO₂ -flood production is the average production before the beginning of CO₂ flooding; post-CO₂ flood production is the average production after the beginning of CO₂ flooding. Pre-waterflood production is the average production before the beginning of waterflooding; and post-waterflood production is the average production after the beginning of waterflooding. Water injected is the average rate at which water was injected during the 4 years following the beginning of waterflooding. CO₂ injected is the average rate at which CO₂ was injected during the 4 years following the beginning of CO₂ flooding.

Pre- and post-waterflood production was compared to pre- and post-CO₂ flood production. The ratio of pre- and post-waterflood production divided by the ratio of pre- and post-CO₂ flood production was the first recognized trend. In Eq. 1, the value C₁ (C₁, C₂, C₃, and C₄ are constants defined in this study) was observed to be constant in most cases.

$$C_1 = \frac{\frac{(Pre-Waterflood Production, STB/D)}{(Post-Waterflood Production, STB/D)}}{\frac{(Pre-CO_2 Flood Production, STB/D)}{(Post-CO_2 Flood Production, STB/D)}} \dots \dots \dots (1)$$

Next, the ratios of fluid injected to fluid produced were analyzed for both CO₂ flooding and waterflooding during the first 4 years of the respective processes. These ratios were then multiplied to optimize the applicability of the constant. In Eq. 2, the term C₂ was found to be constant in most analyzed areas.

$$C_2 = \frac{\frac{(Water Injection, STB/D)}{(Post-Waterflood Production, STB/D)} \times (CO_2 Injection, STB/D)}{(Post CO_2-Flood Production, STB/D)} \dots \dots \dots (2)$$

Eqs. 1 and 2 were solved using the actual production data. An average constant was calculated and used to back-calculate the post-CO₂ flood production. The average percent error using Eq. 1 was 48%. The average percent error using Eq. 2 was 19%.

Combining Eqs. 1 and 2, a third equation was developed that includes both production data and injection data. Eq. 3 was derived by dividing Eq. 1 by Eq. 2. In Eq. 3, the term C₃ was found to be constant in most areas analyzed.

$$C_3 = \frac{\frac{(Prewaterflood Production STB/D)}{(Pre-CO_2 Production STB/D)} \times (Post CO_2 Prod. STB/D)^2}{\frac{(Water Injected STB/D)}{(CO_2 Injected STB/D)}} \dots \dots \dots (3)$$

An average value for C₃ is calculated using actual data. Using the data from the Weyburn, the value of C₃ for various sections of the

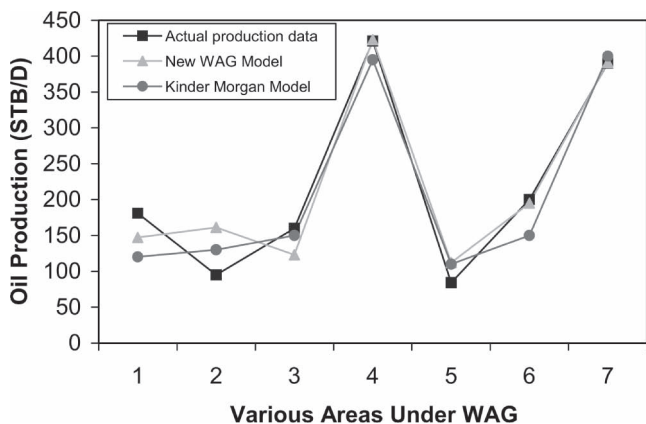


Fig. 3—Comparison between the actual production data with the new model and Kinder Morgan flood-scoping model.

reservoir was determined as 0.001 ± 0.00015 . This indicated that C_3 could be used as a constant for predicting the post- CO_2 flooding oil production. Hence, Eq. 3 was rearranged for calculating post CO_2 flood production as follows:

Post- CO_2 Flood Production, STB/D =

$$\sqrt{\frac{(\text{Pre-}CO_2 \text{ Flood Production, STB/D}) \times (\text{Water Injected, STB/D}) \times (CO_2 \text{ Injected, STB/D}) \times C_3}{(\text{Pre-Waterflood Production, STB/D})}} \dots (4)$$

The correlation in Eq. 4 was used to calculate production rates from seven different areas of the Weyburn where the WAG process had been implemented. The results obtained were compared with actual production data, as well as production rates predicted by the Kinder Morgan technique. Fig. 3 presents the results of such comparison.

The previous analysis shows a very close agreement between the results of the correlation developed in this study and the actual production data. Interestingly, application of the Kinder Morgan flood-scoping tool to predict oil production for these areas led to an average error very similar to the new correlation. The results of an error analysis based on individual areas, as well as the total production, are shown in Table 1.

As mentioned, the Kinder Morgan tool yielded results very similar to those of the developed empirical correlations. The same trends were observed in each of the areas where the Kinder Morgan prediction is usually the most conservative. These trends can

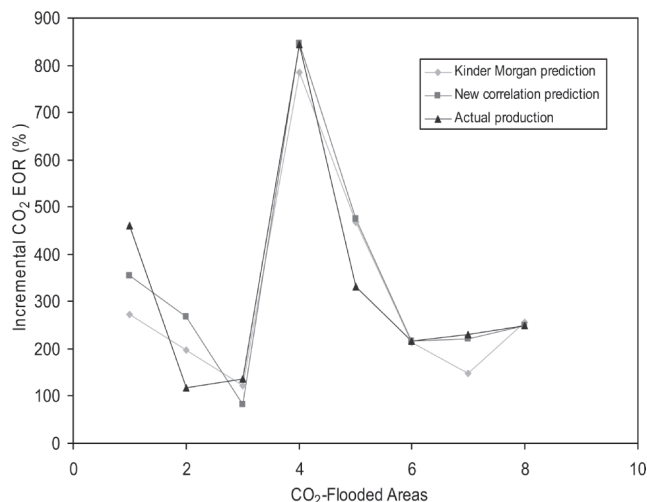


Fig. 4—Percent increase chart (WAG correlation).

TABLE 1—SUMMARY OF WAG PRODUCTION RESULTS

	Area							Total
	1	2	3	4	5	6	7	
Actual Production	181	95	160	421	84	200	390	1,531
WAG Empirical Correlation	147	161	123	423	112	195	391	1,552
Percent Error	19%	69%	23%	0%	33%	3%	0%	1.3%
Kinder Morgan Projection	120	130	150	395	110	150	400	1,455
Percent Error	34%	37%	6%	6%	31%	25%	3%	5%

be seen in Fig. 4. Although the results of the Kinder Morgan tool and the WAG empirical correlation were quite similar, the methods of obtaining them are completely different. Kinder Morgan uses dimensionless variables, while the WAG correlation uses production and injection data. The close match between the Kinder Morgan flood-scoping tool, the developed empirical correlation, and the actual production data proves the validity of using the developed correlation in the Weyburn-Midale oil field.

New Correlations for Horizontal CO_2 -Injection Wells

Not only WAG-vertical wells were implemented in the Weyburn CO_2 project, but horizontal CO_2 injection wells were also implemented. The process differs from the WAG method in several aspects. Primarily, the WAG scheme uses a large number of wells in comparison to the horizontal scheme. This is because the horizontal wells span a length that would normally be occupied by three injection wells in a WAG setup. Also, the WAG process involves injecting water and CO_2 from the same well. Conversely, as presented in Fig. 5, the horizontal well is dedicated to injecting only CO_2 , while an existing vertical well is located between the two horizontal legs for injecting water.

Another difference between WAG and horizontal injectors is the fact that the horizontal injectors do not penetrate into the lower vuggy zone. Instead, the injectors are drilled in the upper marly zone. Overall, the horizontal CO_2 -injection scheme has fewer wells, water, and CO_2 injected simultaneously through separate wells, and greater sweep efficiency.

In the Weyburn field, a total of 15 patterns incorporated horizontal CO_2 -flooding techniques. Typical analytical prediction tools, such as the Kinder Morgan model, do not incorporate horizontal-injection wells. Thus, an empirical correlation is a preferred method for this field. Fig. 6 is a topographical view of the 6 patterns that were chosen to develop a correlation for the patterns with horizontal wells.

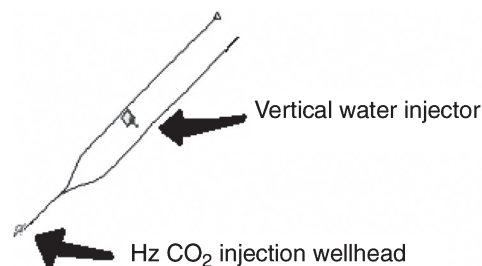


Fig. 5—Horizontal injector set-up.

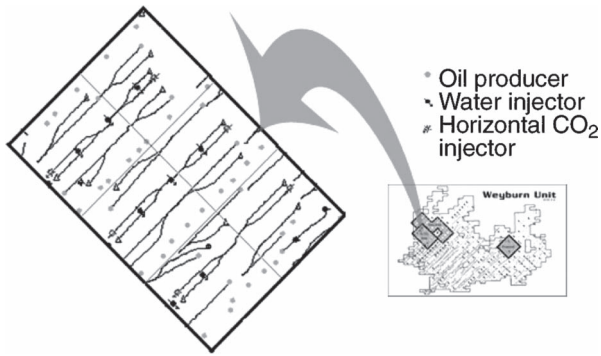


Fig. 6—Areas under simultaneous injection of CO₂ and water into horizontal and vertical wells, respectively.

A correlation was developed to predict the performance of a CO₂ flood using horizontal injectors. This model was used to predict the average oil-production rate for 4 years after the start of CO₂ injection.

The correlation is similar to the empirical WAG correlation but has a slightly different format with the addition of several more inputs. Eq. 5 shows a constant C_{hz} that is a ratio of several 4-year averaged production and injection rates:

$$C_{hz} = (CO_2 \text{ Production} / CO_2 \text{ Injection}) \times (CO_2 \text{ Production} / CO_2 \text{ Pre}) \times (W_{\text{Post}} / W_{\text{Pre}}) \times (W_{\text{Post}} / W_{\text{Injection}}) \quad (5)$$

As can be seen by Eq. 5, a constant for this field has been developed that takes various production ratios into account. The value of this constant was found to be 1.2476×10^{-3} . The use of this constant to predict oil production rates leads to an error of approximately 12%. Considering the simplicity of the correlation, this is an excellent accuracy. For the production prediction purposes, the Eq. 5 is rearranged in the form of Eq. 6.

$$CO_2 = \frac{\sqrt{C_{hz} \times W_{pre} \times W_{inj} \times CO_{2inj}}}{(W_{post}^2)} \dots \dots \dots (6)$$

Because the Kinder Morgan model could not be used for areas with horizontal wells, it was not possible to verify this correlation

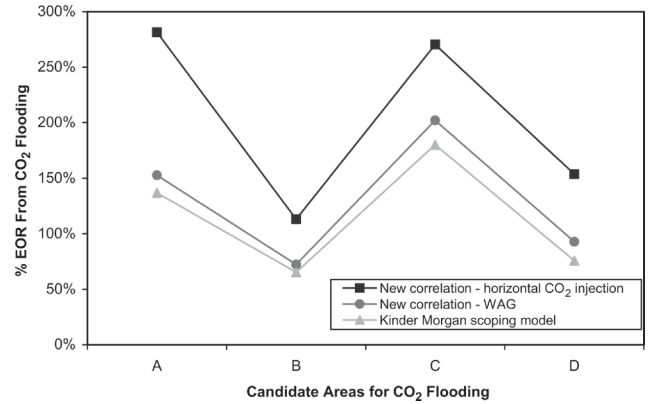


Fig. 7—CO₂ enhanced oil recovery (EOR) percentage of oil production increase in four new candidate areas for CO₂ flooding in the Weyburn field.

against another model. However, the fact that the value of C_{hz} is constant for all areas studied is a good indication that this correlation may be used as a quick way of estimating the oil recovery because of CO₂ injection in horizontal wells in the Weyburn reservoir. Overall, this correlation is an effective scoping tool in predicting the response of a horizontal CO₂ flood in the Weyburn field.

Validation of Correlations Developed

In order to verify the validity of the correlations developed in this study, an area of the Weyburn field that is not currently under CO₂ flooding was selected, and the correlations developed here, as well as the Kinder Morgan flood-scoping model, were used to predict the oil-production rate if CO₂ flooding were implemented in those areas. Fig. 7 presents the percentage increase in oil recovery in these areas as predicted by the Kinder Morgan model and the new correlations.

The previous analysis clearly indicates how closely the correlation developed in this study for the WAG processes follows the Kinder Morgan model for future expansion of CO₂ flooding to other areas of the Weyburn field. Because the Kinder Morgan model is an accepted industry tool, the data presented in Table 2 and Fig. 7 validates the applicability of the simple correlation

Area	A	B	C	D	Average	Total
Horizontal Correlation						
Correlated Production	255	291	188	305	260	704
Incremental Oil	188	155	137	185	166	436
% Increase	281%	113%	270%	154%	205%	163%
WAG Correlation						
Correlated Production	169	236	153	232	197	518
Incremental Oil	102	99	102	111	104	250
% Increase	153%	72%	202%	93%	130%	94%
Kinder Morgan						
Correlated Production	158	226	142	211	184	513
Incremental Oil	91	89	91	91	91	245
% Increase	137%	65%	180%	76%	114%	92%

developed in this paper. As for the predictions of the correlation developed for CO₂ injection into horizontal wells, the Kinder Morgan model cannot be used. A complete validation of this model requires conducting reservoir simulation on the proposed areas. Nevertheless, because the process of developing correlations for both WAG and horizontal wells were similar, it is expected that the correlation for the horizontal wells will be as valid as the one developed for the WAG process.

Conclusions

1. Two relationships were developed to correlate pre-CO₂ flood production data with post-CO₂ flood production data. One for the WAG process with vertical wells, and a second correlation for a scheme involving injection of CO₂ in horizontal wells.
2. The correlations had an acceptable level of error of less than 12%.
3. Kinder Morgan flood-scoping model was used to validate the correlations developed in this paper.
4. Application of new correlations and Kinder Morgan model in an area that has not been under CO₂ flooding yielded similar trends. As expected, the horizontal setup had the largest projected increase.
5. Both of the correlations require some post-CO₂ flood data to develop constants. Thus, an existing CO₂ area is necessary to apply these correlations.
6. These correlations provide a very fast and practical method for determining where to expand an existing CO₂ flood operation.
7. It is quite possible that these correlations are applicable in other oil fields. However, it is assumed that the constants calculated for Weyburn-Midale field are not universal. Rather, each field will most likely have its own unique correlation constants.

Nomenclature

C_{hz}	= horizontal-well constant equivalent to 0.0012476
$CO_{2\text{ injection}}$	= 00–04 CO ₂ - injection volume
$CO_{2\text{ pre}}$	= 96–99 Production-rate average
$CO_{2\text{ production}}$	= 01–04 Production-rate average
$W_{\text{injection}}$	= 65–68 Water-injection volume
W_{post}	= 65–68 Production-rate average
W_{pre}	= 60–63 Production-rate average

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SI Metric Conversion Factors

$$\text{bbl} \times 1.589\,873 \quad \text{E-01} = \text{m}^3$$

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