An analytical model for performance prediction of miscible flooding methods

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ABSTRACT

The main target of this study is to develop fast and efficient analytical model that can predict reservoir performance under the implementation of miscible flooding processes. The developed model uses upgraded fractional flow theories and several areal sweep efficiency models. Unlike previous attempts in this topic, the developed model accounts for reservoir instability factors such as reservoir heterogeneity, viscous fingering behavior and gravity segregation. In addition, it accounts for different Enhanced Oil Recovery (EOR) injection strategies including continuous solvent injection and simultaneous Water Alternate Gas (WAG) injection in both secondary and tertiary miscible displacement modes. Moreover, the model has been extended to account for different injection patterns including line drive and 5-spot. The model was validated against two actual field applications: (1) the WAG injection pilot project of Slaughter field, and (2) the miscible flooding pilot project of Garber field. The results of the model deviate from the results of the field measurements with a range of 7.3 to 20.4%. This match demonstrated the ability and the strength of the developed model. The model utilizes a limited set of input data that is available in the field

at the early stages of the reservoir life. Therefore, it can be used as a pre-simulation tool to support the decision-making during the critical technology selection phase.

Keywords: Analytical model; Chemical flooding; Miscible flooding.

INTRODUCTION

Recently, great efforts have been carried out to develop analytical models that can perform screening and predict the performance of the EOR technologies (El-Tayeb et al., n.d.; Nageh et al., 2015). The analytical models are helpful especially for the applications of the miscible flooding at early stages of the solvent injection as the accuracy of the numerical simulation at this stage could be hindered by the lack of necessary parameters invoked by the solvent injection into the reservoir. These models can be used as a dependable tool in the early stages of the miscible flooding process.

Several analytical models of miscible flooding exist in the literature. Initially, Koval upgraded the Buckley-Leverett fractional flow equation to obtain a representation of the fractional flow between miscible components in the oleic phase (oil and solvent components) (Koval, 1963). His derivation was made for line drive patterns and included the effects of viscous fingering and reservoir heterogeneity on miscible flooding behavior. Then, Claridge provided a transformation of Koval’s work for a seamless application in five-spot patterns (Claridge, 1972). It should be highlighted that Koval and Claridge models are only applicable in the secondary recovery stages. In other two studies, Paul et al. introduced a more integrated model that incorporates the chromatography theory (Paul, G. W., Lake, L. W. and Gould, 1984; Paul G.W. and Ray, 1984). Additionally, their model has the ability to account for secondary and tertiary miscible displacements. However, the model is limited to five-spot pattern only.

Later, Walsh and Lake (Ghanbarnezhad-Moghanloo and Lake, 2012) outlined an edited application of Buckley-Leverett theory for miscible flooding as the fourth analytical model. The immiscible nature of water and solvent along with water and oil was exploited in their simpler derivation. However, their deduction focused only on microscopic factors. Applying their theory for real applications requires accounting for other factors to represent upscaled displacement behavior through considering viscous fingering, channeling, dispersion and gravity segregation. Recently, other two models were introduced by Mollaei (Mollaei, 2011; Mollaei and Delshad, 2011a, 2011b) and Jain (Jain, 2014; Jain and Lake, 2014, 2013). Mollaei developed a novel theory that is based on Koval's proposition. Then, Jain upgraded Mollaei's formulation and integrated it with the chromatography theory.

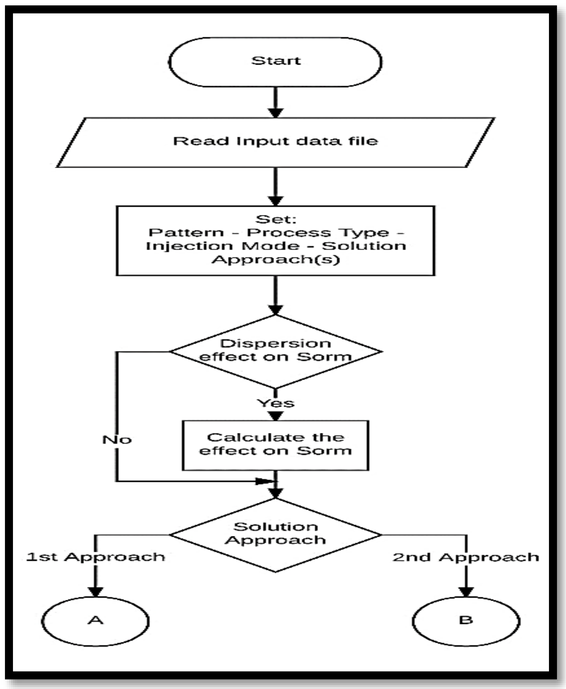
Obviously, there is no model that accounts for all the factors affecting the miscible flooding process. The older models (Koval, Claridge, Walsh and Paul models) assumed a diffuse type of flow in their derivation while being only applicable to a specific injection pattern. On the other hand, the recent models (Mollaei and Jain models) considered segregated flow conditions. Therefore, the main target of this work is to incorporate all possible effects on miscible flooding recovery into a wide scoped, rigorous, integrated and robust analytical model. These factors include reservoir heterogeneity, gravity segregation, viscous fingering, and dispersion. The different injection patterns (5-spot or line drive), modes (secondary or tertiary) and strategies (Continuous and WAG) are, also, accounted in the developed model.

MODEL ALGORITHM

The structural of the developed model is shown in **Figure 1**. The model includes calculations procedure for the following:

- *The residual oil saturation at the end of the miscible flooding* – This subroutine resembles the effects of the loss of miscibility and dispersion on the residual oil saturation remaining at the end of miscible flooding. The curves of Moghanloo (Ghanbarnezhad-Moghanloo and Lake, 2012; Moghanloo, 2012) are used for this purpose

- *The relative permeability data* - The relative permeability data can be inserted as data points, and the program will thereafter fit the data points to Corey's correlations (Corey, 1954; Honarpour et al., 1986).
- *The combination procedure of the displacement and areal sweep efficiencies*



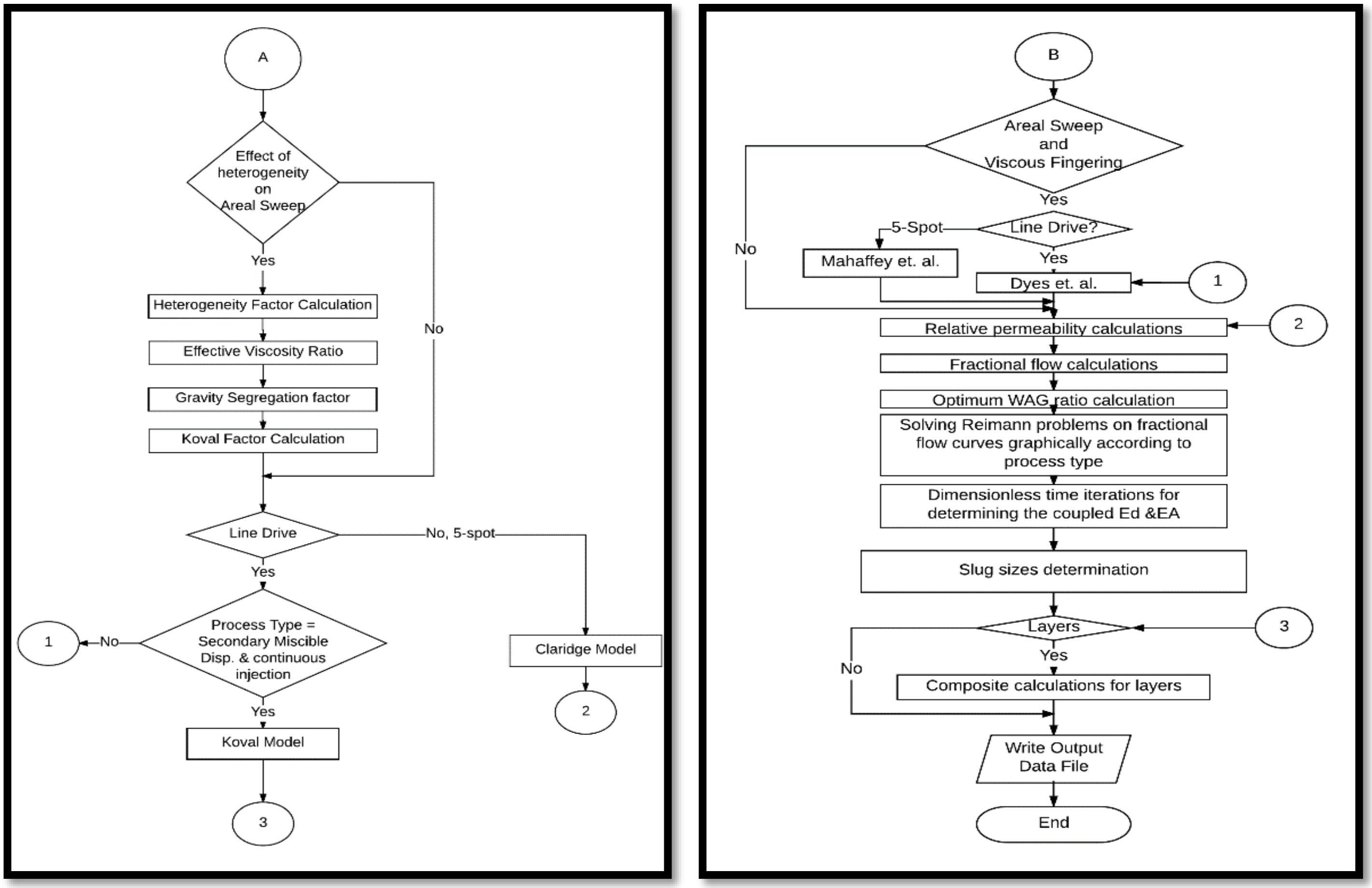


Figure 1 – Structure of the developed model

** 1, 2 and 3 in the figure of the right side represent a continuation to the calculations which are presented in the figure of the left side.*

In order to combine the different time scales from the fractional flow theory and areal sweep models, the following steps solution for tertiary recovery was used. For secondary recovery, the multipliers in the table would be set to one and pseudo dimensionless times would equal their corresponding dimensionless times.

Step	**Equation**	**Eq. #**
1. The dimensionless breakthrough time from the fractional flow theory ($t_{D1\,(BT)_{OB_f}}$) is calculated from the front velocity v_{OB_f} and assuming a dimensionless distance of 1 (X_D =1 at the production well)	$t_{D1\,(BT)_{OB_f}} = \frac{X_D}{v_{OB_f} * \text{Multiplier}} = \frac{1}{v_{OB_f} * \text{Multiplier}}$ Where: Continuous Injection Multiplier $= 1 - S_{orm} - S_{ws}$ WAG Injection Multiplier $= 1 - S_{orm}$	1

2. $t_{D1\,(BT)_{OB_f}}$ is then transformed into a pseudo time value

$$\grave{t}_{D1} = \frac{\text{Volume of solvent injected}}{\text{movable volume by the injected solvent}} + \frac{\text{volume of oil in the oil bank above } S_{oI}}{\text{movable volume by the injected water}} = t_{D1} * \left(1 + \frac{S_{oI} - S_{orm}}{S_{o(OB)} - S_{oI}}\right) \tag{2}$$

3. The dimensionless breakthrough time from the areal sweep efficiency model ($t_{D2\,(BT)}$) is transformed to its pseudo $\grave{t}_{D2}$

$$\grave{t}_{D2} = t_{D2} * \left(1 + \frac{S_{oI} - S_{orm}}{S_{o(OB)} - S_{oI}}\right) \tag{3}$$

4. Total pseudo dimensionless time and rates are estimated

$$\grave{t}_{D\,(BT)} = \grave{t}_{D1\,(BT)} * \grave{t}_{D2\,(BT)} \tag{4}$$

5. The time step is increased to a value greater than $\grave{t}_{D\,(BT)}$. $\grave{t}_{D1}$ is assumed at a value greater than $\grave{t}_{D1\,(BT)}$. t_{D1} is calculated as a function of $\grave{t}_{D1}$ by rearranging Equation 4. 5

6. Average saturations behind the front are evaluated using multipliers that are case specific values determined from the work of Walsh and Lake, 1988

$$\bar{S}_o = S_{o\,(X_D=1)} - t_{D1} * \left(f_{o\,(X_D=1)} - f_{oJ}\right) * \text{Multiplier} \tag{6}$$

$$\bar{S}_w = S_{w\,(X_D=1)} - t_{D1} * \left(f_{w\,(X_D=1)} - f_{wJ}\right) * \text{Multiplier}$$

$$\bar{S}_s = 1 - \bar{S}_o - \bar{S}_w$$

Where $S_{o\,(X_D=1)}$, $S_{w\,(X_D=1)}$, $f_{o\,(X_D=1)}$ and $f_{w\,(X_D=1)}$ are determined through the constructed fractional flow path as described by Walsh and Lake, 1988.

7. Evaluate pseudo $\grave{t}_{D2}$ at the new time step $\grave{t}_D$

$$\grave{t}_{D2} = \frac{\text{Actual and assumed injected volumes}}{\text{Their equivalent saturation}} = \frac{\grave{t}_D}{\bar{S}_o + \bar{S}_s + S_{w_{WAG}}} \tag{7}$$

8. Estimate the $E_{A_{\text{oil Bank}}}$ from Mahaffey/Claridge model and recalculate $\grave{t}_{D1}$

$$\grave{t}_{D1} = \frac{\text{Actual injected volume}}{\text{fraction of area invaded by solvent and oil}} = \frac{\grave{t}_D}{E_A} \tag{8}$$

The error in $\grave{t}_{D1}$ is estimated. If the error is large, the calculation is re-iterated. Once the error is small, the time step $\grave{t}_D$ is increase for new time step. To calculate the rates at and beyond the solvent front, the method of Walsh and Lake 1988 is employed.

The calculations considered, also, the possibility of the existence of stratified reservoirs. The stratification is incorporated through an edited version of previous equations. In the method of Craig-Geffen-Morse (Ahmed, 2010; Craig et al., 1955), a base layer is selected first, and its performance is calculated. A base layer would be a layer having the highest capacity (formation permeability multiplied by its thickness) among all layers. Then, the performance of the rest of the layers is related to the base layer's performance.

The developed model was programmed using C# programming language. The last step in the model is to extract the output data and projected future performance as a function of time. Under a specific condition and type of injection scenario, the model can predict the following parameters with time: (1) oil, water and solvent production rates; (2) water cut; (3) cumulative production of oil, water and solvent; (4) fractional flow curves; (5) optimum WAG ratio; (6) minimum slug size; and (7) residual oil saturation at the end of the miscible flooding process.

MAIN CONCEPTS AND THEORIES OF THE MODEL

In this work, the fractional flow theory was used to evaluate the displacement efficiency of the miscible flooding process. Two versions of the modified fractional flow theory were utilized and compared: the pixel scaled version of Walsh (Walsh and Lake, 1989) and the window scaled version of Koval (Koval, 1963). Since the displacement efficiency represents the amount of a displaced component relative to its contacted amount, it's not sufficient; and there is a need to relate the contacted amount of the component to the initial amount in place. This is what the areal sweep efficiency does. Therefore, the areal sweep efficiency models of Mahaffey et al. (Mahaffey et al., 1966), Dyes et al. (Dyes et al., 1954) and Claridge (Claridge, 1972) are considered.

A combination procedure for binding the fractional flow theory and the different areal sweep models was formulated to bring the use of the fractional flow theory closer to field wide applications. In addition, the curves of Moghanloo (Ghanbarnezhad-Moghanloo and Lake, 2012; Moghanloo, 2012) were modeled to resemble the combined effects of the dispersion and loss of miscibility on the residual oil saturation remaining at the end of the miscible flooding. Moreover, the gravity segregation factor correlations of Paul et al.(Paul, G. W., Lake, L. W. and Gould, 1984) and the heterogeneity factor of Koval (Koval, 1963) were combined in the model to fit the field applications and achieve the model objectives and considerations. The considered paths in the proposed model are presented in **Figure 2**.

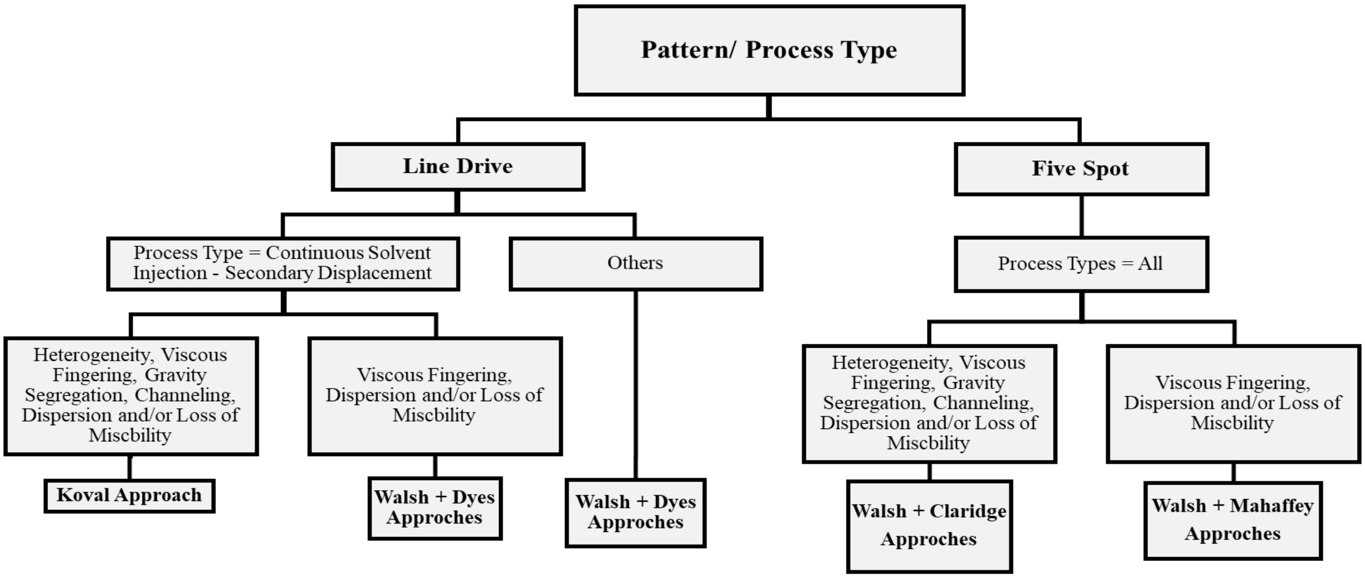


Figure 2 - Scenarios of the developed model

MODEL ASSUMPTIONS

The main assumptions of the proposed model include the following: (1) Isothermal porous medium, (2) Independency of fluid properties on pressure, (3) Ideal mixing of fluids (Fluids don't interact with the solid phase), (4) Presence of only oil and water at initial conditions though the presence of gas can be alleviated by normalizing oil and water saturations as an approximate solution, (5) Simultaneous injection of either water with solvent or water with chase fluid in WAG mode, (6) Full miscibility (First contact miscibility) of the two components, solvent and oil, in the oleic phase, (7) Sufficiently large slug sizes are used to avoid wave interference between the chase fluid and the oil bank in order to prevent additional oil trapping and therefore a lower displacement efficiency, (8) Equality of the two-phase relative permeability between solvent and water to that between oil and water, although different permeability can be inserted and modelled similarly, (9) Efficiency of Koval factor in capturing the effects of reservoir heterogeneity, viscous fingering and gravity segregation, and (10) Residual oil saturation to miscible flooding is only affected by longitudinal dispersion and loss of miscibility around wellbore.

MODEL CAPABILITIES

Compared with the other predictive models, the developed model has the ability to deal with the effects of reservoir heterogeneity along with gravity segregation, dispersion, loss of miscibility and viscous fingering behavior. It also accounts for different EOR injection strategies including continuous solvent injection and simultaneous WAG injection in both secondary and tertiary miscible displacement modes. Moreover, the model has been extended to account for the different patterns including line drive and 5-spot.

MODEL VALIDATION AND FIELD APPLICATIONS

The developed program was run against the published data of two actual field applications (Ader and Stein, 1984; Kumar and Eibeck, 1984; Rowe et al., 1982): the WAG injection pilot project of Slaughter field in Texas (WAG injection project), and (2) the miscible flooding pilot project of Garber field in Oklahoma (continuous solvent slug injection project).

1. Model validation using published data of Slaughter field (WAG injection pilot project)

The WAG pilot project in Slaughter field (Slaughter Estate Unit - SEU) consists of two adjacent five-spot patterns with an area of 12.29 acre (Ader and Stein, 1984; Rowe et al., 1982). The project included six injectors and two producers as two injectors were at the boundary of the two adjacent five-spot patterns (the two injectors are common in the two patterns). The OOIP in the pilot patterns was approximately 642,400 STB. **Table 1** presents the summary of the average reservoir properties in the pilot area (Ader and Stein, 1984; Rowe et al., 1982). The waterflooding commenced in the pilot area starting from 1972 and continued till 1976. The alternate solvent gas and water injection (miscible flooding) was thereafter implemented in Aug. 1976. Stabilized water injection rates were approximately 400 BWPD per well immediately before solvent gas injection.

The miscible injection mode in the pilot was WAG process. The injection was done in cycles between the 6 injection wells. At any time, three wells were used for injecting the solvent, and the other three wells were used for injecting the water. The cycles were reversed several times between the six wells. Accordingly, in the subsequent cycle, the injected fluid in each well was reversed from water to solvent and vice versa. The cycles were reversed several times in the actual field. However, the developed program entails a simultaneous injection of water and solvent in the WAG mode as the schedule of the injection is not crucial in the model. The water was injected with an average rate of 460 bbl/d for each water injector. However, the average solvent gas injection rate for each gas injector was 550 Mscf/D (Ader and Stein, 1984; Rowe et al., 1982). The composition of the miscible solvent gas was 72% CO_2 and 28% H_2S since obtaining pure CO_2 was not attainable for this project. The solvent gas was injected into the pilot area through Oct. 1979. In Nov. 1979, nitrogen chase gas injection was initiated. An interruption in the pilot's nitrogen supply in April 1980 forced a temporary change to residue chase gas injection until Dec. 1980 when nitrogen injection was resumed.

Table 1. Data of Slaughter field (Ader and Stein, 1984; Rowe et al., 1982)

Input Parameter	**Value or Description**
Injection mode	WAG injection of CO2 and H2S
Pattern	Double five-spot
Pattern area, Acre	12.29
Reservoir depth, ft	4,985
Reservoir temperature, ºF	105
Net pay, ft	75.2
Permeability to oil at connate water saturation, md	6.4
Oil formation volume factor at original bubble point, Res bbl/STB	1.228
Connate water saturation, % PV	8.1
Average reservoir pressure during tertiary flood, psi	2,200
Oil viscosity at average reservoir conditions, cp	2
Water viscosity at average reservoir conditions, cp	0.7
Solvent viscosity at average reservoir conditions, cp	0.074
Residue gas viscosity at average reservoir conditions, cp	0.016
Nitrogen viscosity at average reservoir conditions, cp	0.022
Oil density at average reservoir conditions, lb/ft^3	51.4

Water density at average reservoir conditions, lb/ft^3	62.4
Solvent gas density at average reservoir conditions, lb/ft^3	46.3
Residue gas density at average reservoir conditions, lb/ft^3	7.5
Nitrogen density at average reservoir conditions, lb/ft^3	9.0

The developed program was run using the data of Slaughter field pilot project to predict the performance of the miscible CO_2 flooding project. Based on the conditions of the five spot patterns, two different scenarios were used to run the developed program. Scenario 1 is based on the Walsh and Mahaffey approaches (Walsh approach refers to the fractional flow theory and Mahaffey approach is used for the areal sweep model); while the second scenario (Scenario 2) is solved using Walsh and Claridge approaches (Walsh approach refers to the fractional flow theory and Claridge approach is used for the areal sweep model). As shown in **Figure 3**, the oil production rates and the cumulative oil production of the two scenarios are compared with the actual field measurements. The comparison shows good match between the actual performance of the reservoir and the predicted results of the developed model (two scenarios).

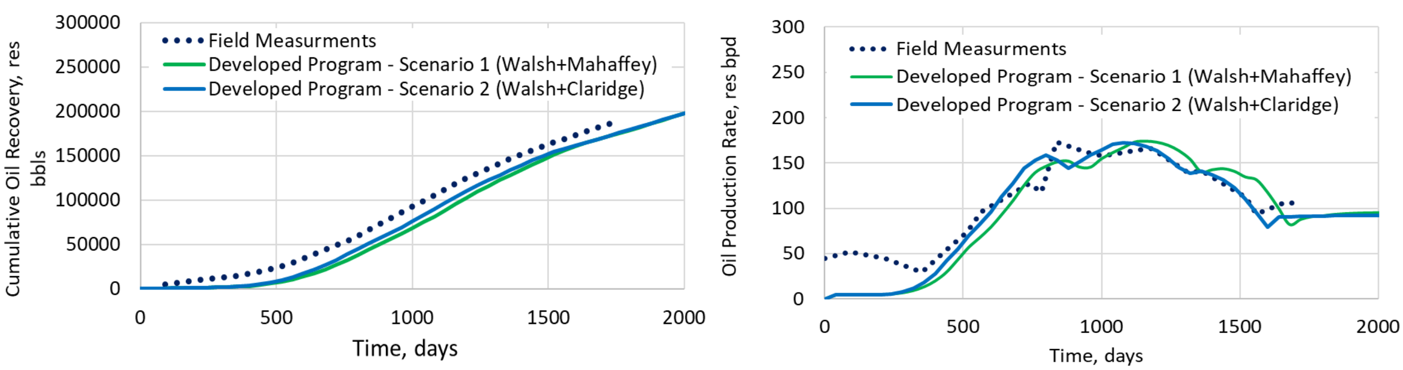


Figure 3- Performance curves of the pilot project of Slaughter field

2. <u>Model validation using published data of Garber field (CO2 miscible flooding pilot project)</u>

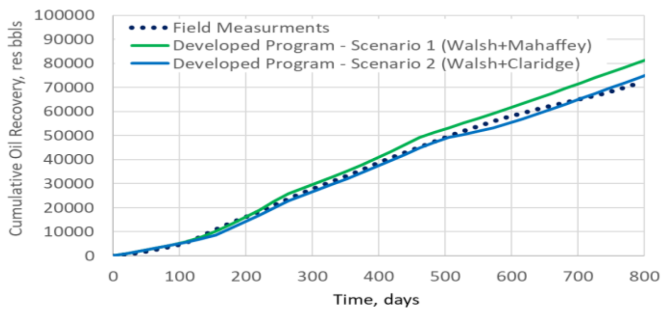
The CO_2 miscible flooding pilot project of Garber field consists of one production well in the middle surrounded by four injection wells forming a classic five-spot pattern. In addition, the five-spot pattern is surrounded by eight production wells (Kumar and Eibeck, 1984). The pilot effective area is 38.3 acres, while the area of the 5-spot pattern is 10.4 acres. The field was waterflooded and later the CO_2 was selected as miscible agent. The solvent slug was injected continuously into the four injection wells. The injection of the solvent into the pilot started in October of 1981. Total of 27,000 tons of CO_2 was injected as a straight slug. The gross daily injected CO_2 volumes varied between 110 and 120 tons/day. The field data is presented in **Table 2** (Kumar and Eibeck, 1984).

The developed model was run using the data of the pilot project of Garber field using two different scenarios as well. The first scenario represents Walsh and Mahaffey approaches (Walsh approach refers to the fractional flow theory and Mahaffey approach is used for the areal sweep model). However, the second scenario includes Walsh and Claridge approaches (Walsh approach refers to the fractional flow theory and Claridge approach is used for the areal sweep model). The results (oil production rates and the cumulative oil production) of the runs of the two scenarios are compared to the published field measurements. **Figure 4** shows a good match between the results of the developed predictive model (two scenarios) and the field measurements.

Table 2. Data of the CO2 pilot project - Garber field (Kumar and Eibeck, 1984)

Input Parameter	Value or Description
Injection mode	Continuous injection of CO_2
Pattern/ Pattern area, Acre	Five-spot/ 10.4
Effective pilot area, Acre	38.3
Formation	Crews Sandstone
Depth, ft	1950
Depth subsea, ft	-900
Formation dip, Degrees	<5
Average net pay, ft	21
Average porosity, % PV / Average permeability, md	17%/57md
Initial connate water saturation, % PV	30
Reservoir temperature, ºF	95
Original formation volume Factor, RB/STB	1.2

Oil gravity, API / Oil viscosity, cp	47 API/2.1cp
Original oil-in-place in the effective area, STBO	620,000
Average reservoir pressure at the start of CO_2 injection, psi	1250
GOR at the start of CO_2 injection, SCF/STBO	14
Estimated oil saturation at the start of CO_2 injection, % PV	25-30%
Minimum miscibility pressure, psig	1075
CO2 formation volume factor @ 1250 psig & 95 ºF, Res Bbls/MCF	0. 5546



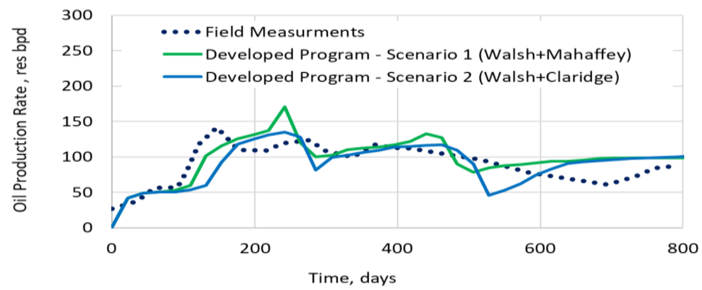


Figure 4 - Performance curves of the pilot project of Graber field

DISCUSSION

It is clear from **Figures 3** and **4** that the results of the developed model are consistent and close to the actual field measurements. In addition, it is obvious that the results of Scenario 1 of Walsh and Mahaffey approaches was quite in conformance with the corresponding results of the second scenario of Walsh and Claridge approaches in most cases of the five-spot pattern. The average absolute deviation between the actual measurements and the corresponding predicted results of the two scenarios in the two field applications ranges between 7.3 to 20.4% as presented in **Table 3.** This match demonstrated the ability and the strength of the proposed model to predict the performance of different injection mode (Continuous injection or WAG processes).

Table 3. Accuracy of the model results in the two field applications

Description	WAG Pilot Project of Slaughter Field	CO_2 Pilot Project of Garber Field
The average absolute deviation for Scenario 1	12.2%	19.8%
The average absolute deviation for Scenario 2	7.3%	20.4%

CONCLUSIONS

1. An analytical model for predicting the performance of miscible EOR processes was developed. The developed model takes into account the effects of heterogeneity, viscous fingering, gravity segregation and dispersion on the flooding efficiency.
2. The model was run against published data of two actual field applications: the WAG injection pilot project of Slaughter field in Texas (WAG injection), and (2) the miscible flooding pilot project of Garber field in Oklahoma (continuous solvent slug injection). The results of the developed model are consistent with the actual field measurements.
3. The results of the model deviate from the results of the field measurements in the two field applications only within a range of 7.3% to 20.4% only.

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