PROCEEDINGS
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An Innovative Modeling Approach to Predict Waterflooding Performance in a Depleted Reservoir with Commingled Production

Silvya Dewi Rahmawati[1], Luky Hendraningrat[2], Dian Nurcahyono[3]
[1]Institut Teknologi Bandung
[2]IATMI
[3]Petro Nusa Profesional

Abstract

Waterflooding is a common technique to improved oil recovery, called as secondary oil recovery method. Predict the waterflooding performance in depleted and dipping reservoir which has completed with commingled production method is challenging in this study.

We introduce a workflow as an innovative modeling approach to design and predict waterflooding performance, includes analytical and mechanistic modelling in in depleted and dipping complex reservoir geology. Rock properties modeling were constructed as top-down method in the mechanistic model.

The results were outstanding and achieved pressure data and oil recovery matching as a modeling validation. This modeling approach can explain the mechanism how reservoir was being produced and why oil recovery is low and conclude whether a room to improve oil recovery. It can be used to design and predict injection performance.

This approach can be classified as an innovative method to have better reservoir management especially in a depleted reservoir with low oil recovery and limited surveillance data.

Introduction

Waterflooding is the common technique to improve oil production and increase oil reserves. It will be more challenging when waterflooding was started below saturation pressure. We observed three main challenges. First, operating below the bubble point pressure triggers gas evolvement out of the oil solution. Second, oil viscosity increases due to gas evolving out of solution, fast reservoir pressure declines i.e. losing reservoir energy if gas flows easily out of the reservoir. Third, subsidence might also occur in the case where rock compressibility is relatively large. In addition, it is a matured field with non-associated gas and complex reservoir geology high properties variation, dipping reservoir, commingled production system from multiple zones, and sparse production allocation. By these situation, direct technique of using full-field modelling cannot be done straightforwardly. In most cases, engineers were utilized the available model and perform the numerical study without properly evaluated all available data and understand the mechanism itself. Hence, the objective of the study is investigating an improve oil recovery potential using waterflooding in depleted and dipping reservoir which has completed with commingled production. The understanding of the mechanism is also important and why current oil recovery is low (~10%) from targeted oil zone with consists of non-associated gas and complex reservoir geology with oil rim that being produced commingled with other upper and lower zones, depleted and dipping reservoir, commingled production and reservoir compartmentalized.

Methodology

We propose an innovative approach to resolve these complexities as shown in Figure-1. At the beginning, we evaluated all available data both laboratory data (core and PVT data) and modeling data from targeted reservoirs. We investigated what is the issue in this study. Second, we evaluated all input data for modeling i.e. rock properties, PVT for targeted reservoir only because current numerical model consisted of multiple completed zones. The main important and most of engineers missed is evaluating the fractional flow from native cores data. However, the condition for most coreflooding is in 2-phase, oil and water. Then, analytical model was developed to understand the mechanism and validated the data of fractional flow. Hence, sensitivity studies can be done once it’s matched. The mechanistic model is constructed to approach real reservoir condition. In this study, the validation has done with observed pressure data as a most reliable data. In term of prediction purposes, several waterflooding scenarios have been studied.

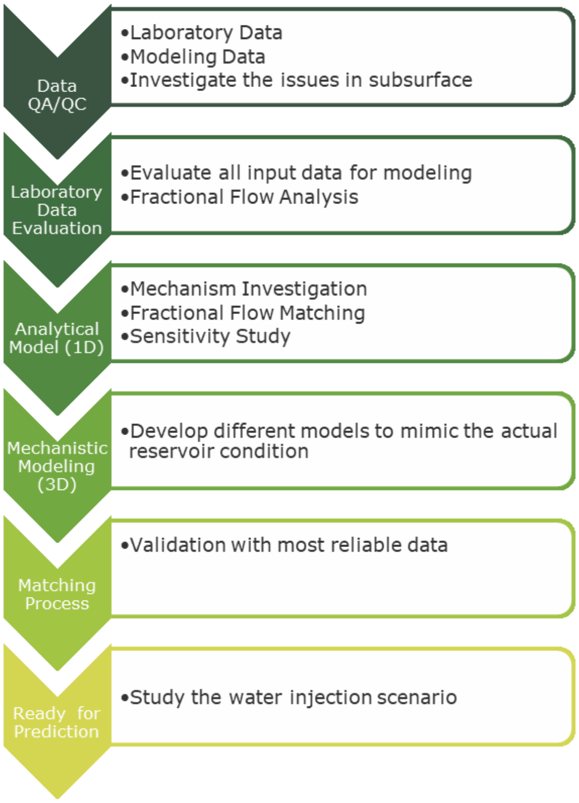

Figure 1 – An Innovative Modeling Approach to Predict Waterflooding Performance in Complex Reservoir

Result and Discussion

Fractional Flow Analysis

Five samples from targeted zones have been investigated and evaluated for this study. Relative phase permeability is the basic function which determine the efficiency of the waterflooding. The accurate laboratory determination of these functions from the routine coreflooding procedure is an important problem of applied reservoir engineering. By knowing each endpoint, water saturation at breakthrough (Sw_{BT}), we can simplify the equation to calculate recovery factor (RF), mobility ratio (M) and displacement efficiency (Ed) using following equations:

$$RF = \frac{Sw_{BT} - Swi}{1 - Swi} \tag{1}$$

$$M = \frac{\frac{Krw_{@SwBT}}{\mu_w}}{\frac{Krow_{@Swc}}{\mu_o}} \tag{2}$$

$$Ed = 1 - \frac{Sorw}{Soi} \tag{3}$$

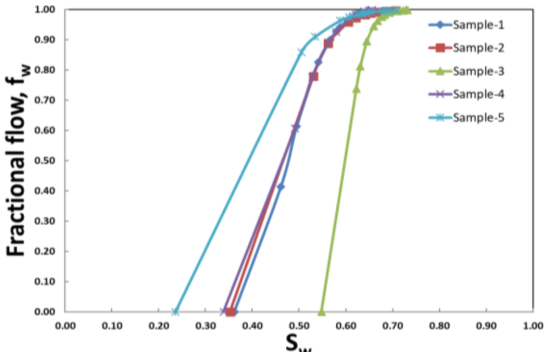

Figure 2 – Fractional Flow Analysis

Table-1 tabulates all calculation from all available samples and implies that the recovery ranges from 22% to 41%. In addition, mobility ratio for all samples are below than 1.0 which implies most oil produced at low water cuts and having high sweep efficiency because it is stable and piston like displacement in horizontal flow. We have to understand that the experiments of these waterflooding were performed on 2-phase flow: oil and gas and above saturation pressure with constant injection rate, which was different with actual condition. Hence, the analytical 1D model was developed to have better understanding what the impact of injecting below saturation pressure is.

Table 1 – Calculation of Recovery Factor, Mobility Ratio and Displacement Efficiency

Sample	RF @ Sw BT %	M	Ed %
Sample-1	34.0	0.71	42.7
Sample-2	35.2	0.54	51.4
Sample-3	22.7	0.92	41.0
Sample-4	36.9	0.49	42.0
Sample-5	41.0	0.59	58.4

Analytical Model

The 1-dimension model was developed with maintaining the pressure above the bubble point, wherever pressure support by water injection. This strategy allows high production rates without risking damage to the reservoir through gas evolution. As shown in Figure-3, in this case, it is assumed no capillary pressure structural relief and ignoring capillary pressure gradients across the system, the equation simplifies to this common form as below:

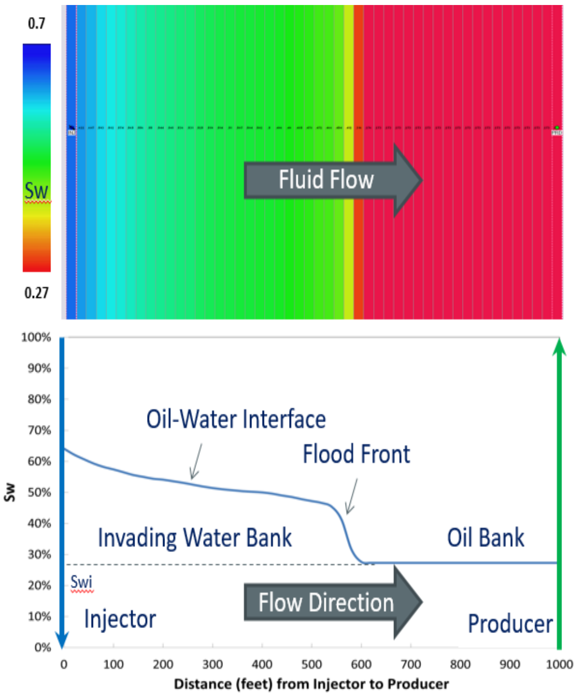

Figure 3 – Analytical Model (1D) with saturation map at particular timestep above bubble point pressure

Measurements of the water cut during the displacement allow to calculate the fractional flow function from analytical model. As shown on Figure-4, the fractional flow matching between core and analytic model has been achieved a good matched in order to check the consistency of endpoint data.

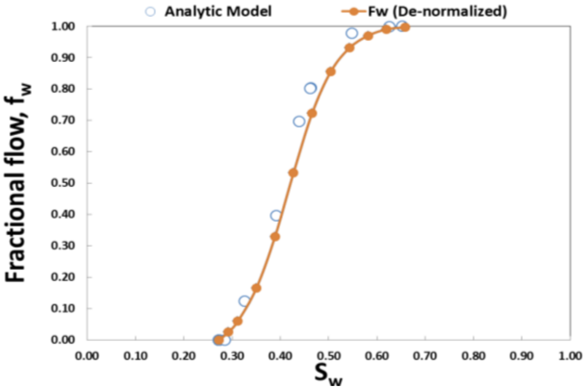

Figure 4 – Fractional Flow Matching between core and analytic model

After having a good matched, analytical model can be utilized to simulate, explain, and make predictions about the mechanisms with different condition such as below bubble point pressure as actual as shown in Figure-5.

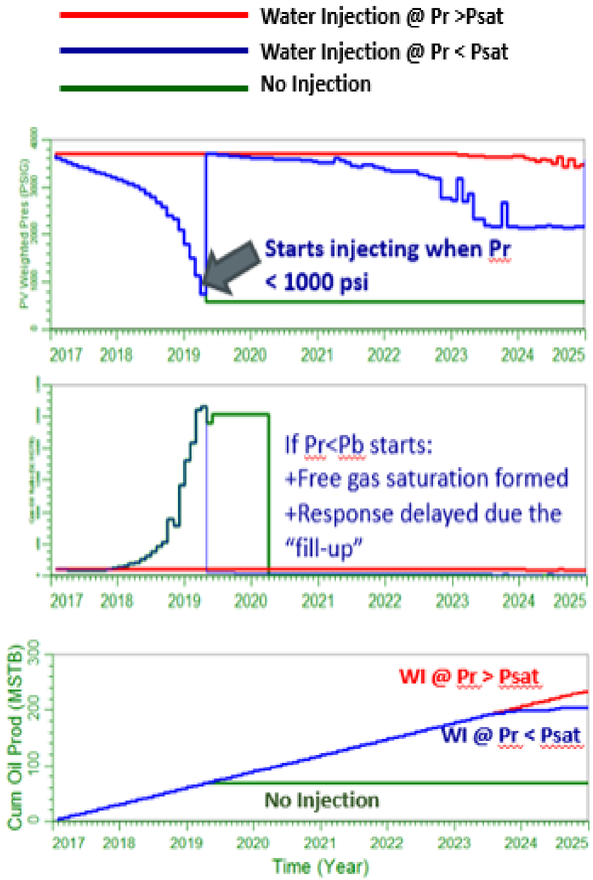

Figure 5 – Production and Pressure Profile of three different scenarios: Injection above bubble point pressure, Injection below bubble point pressure and no injection at all.

It shows that oil production when injection below bubble point is lower than above bubble point pressure. Dyes (1954) described three main mechanisms as follow:

1. Oil depletion from water unswept reservoir volumes. Conventional waterfloods typically sweep the backbone of the reservoir i.e. preferred channels or communication paths where some fraction of the volume is not produced. Meanwhile, solution gas drive pushes the oil from these unswept reservoir regions.
2. Flow interference between the three phases, which results in preferential oil flow. The presence of gas slows down water flow and increases oil flow.
3. Fluid composition changes which lead to the formation of emulsion flow or foamy oil, which are conditional to the oil properties.

Several important parameters are studied such as dipping angle up to 10 degrees. Figure-5 and Figure-6 shows the impact of dipping to fractional flow and injection performance.

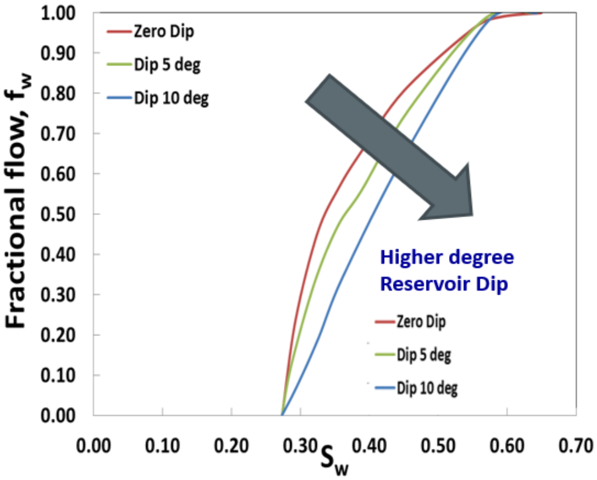

Figure 6 – Effect of formation dip into Fractional Flow

The effect of formation dip is dictated by the gravity term and give better displacement as shown in Figure-7.

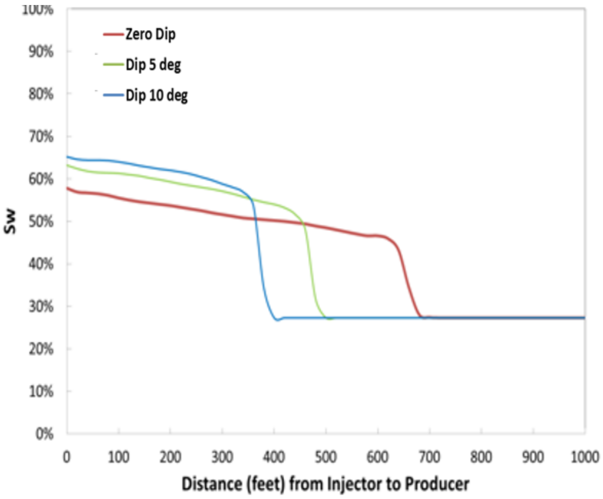

Figure 7 – Effect of formation dip into oil displacement

Mechanistic Model

The 3-dimension and fine grid models were developed with different permeability distribution as main uncertainty in the geomodel. It was distributed as top-down method in the mechanistic model and kept similar volume for all models. Figure-8 shows single number model based on average permeability (300 mD), truncated log normal model based on matching from core data (low permeability) and truncated log normal based on P50 at 300 mD (high permeability), respectively.

We introduce the plot between observed pressure surveillance data and cumulative production oil, represented in oil recovery. The mechanistic model can investigate the mechanism how reservoir was being produced and the most matched data is from truncated log normal high permeability distribution with blowdown the gas cap after produced at particular time (Figure-9) and this story was similar with actual field history. Then, this model is used for prediction purpose i.e. design injection scenario. Based on latest timestep of saturation map, there is a room to improve the oil production through waterflooding process (Figure-10).

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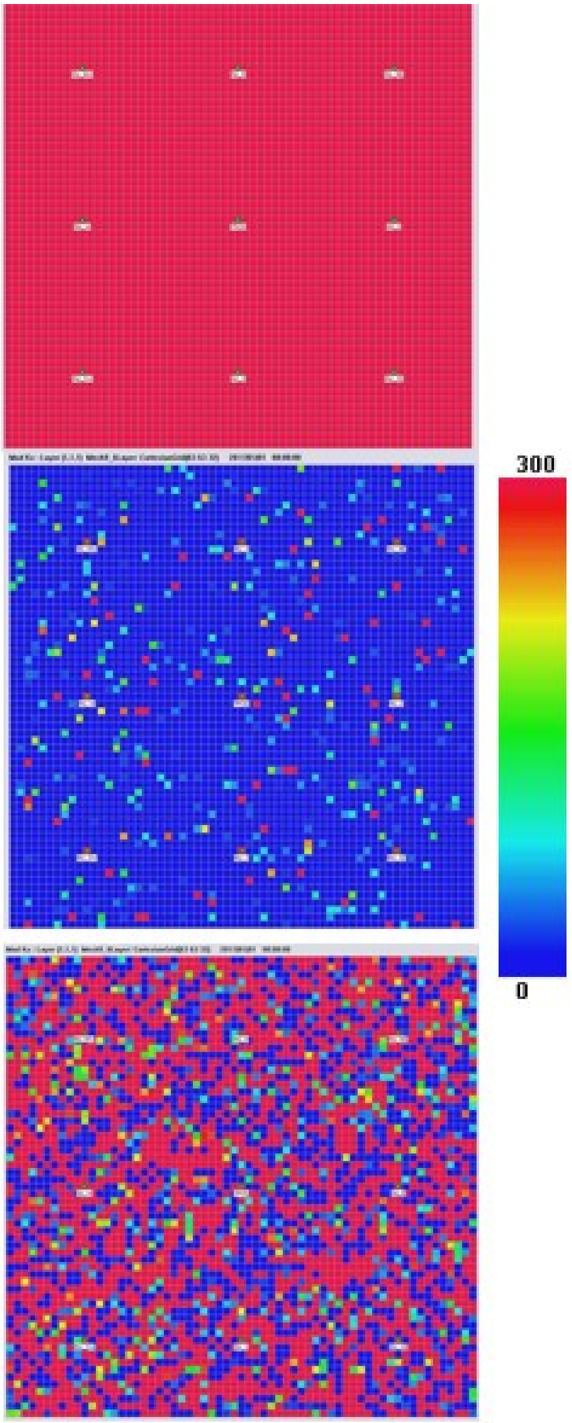

Figure 8 – Permeability distribution models: Single number model based on average permeability (300 mD), log normal model based on matching from core data and log normal based on P50 at 300 mD, respectively.

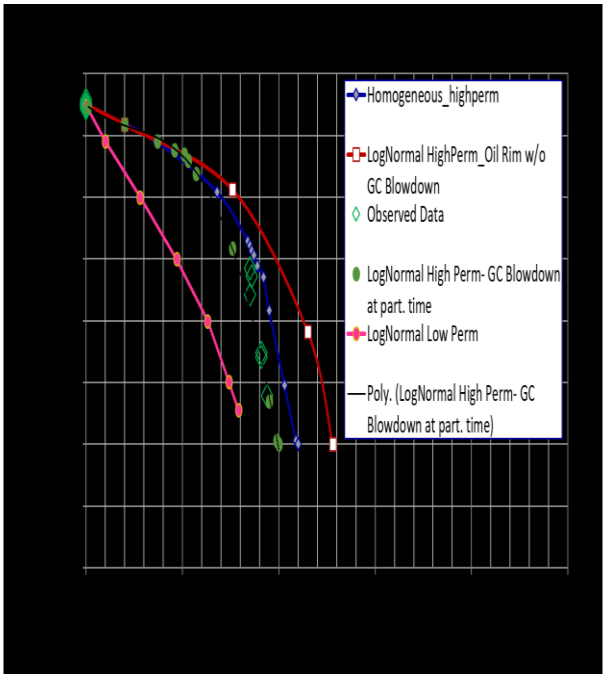

Figure 9 – Matching process between reservoir pressure data and oil recovery from different model

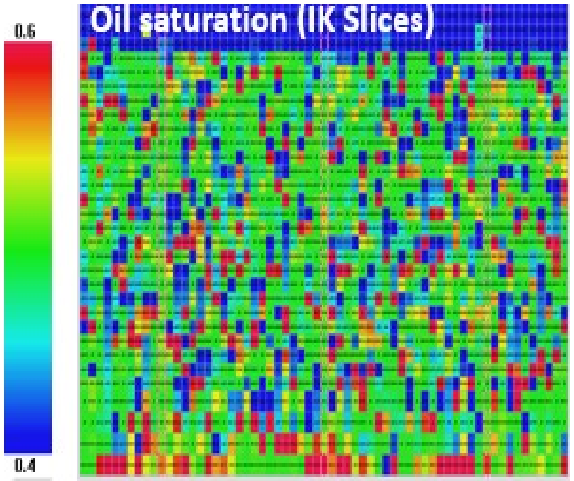

Figure 10 –Oil saturation map at latest timestep

Improve Oil Recovery

In this part, several injection scenarios were design to maximize oil recovery. Several water injection patterns are designed as follow: Line drive (1- and 2-line), 5-spot pattern (Regular and Inverted), 9-spot pattern (Regular). The bottom hole pressure and injection rate are set as similar with constraint from actual field. Figures 11 to 15 show the oil saturation map after 1.5 pore volume of injection. Based on numerical modeling, there is a room to improve oil recovery from targeted zone by waterflooding process with range of improvement from 4 to 11 %. The most effective scenario is coming from inverted 5-spot pattern.

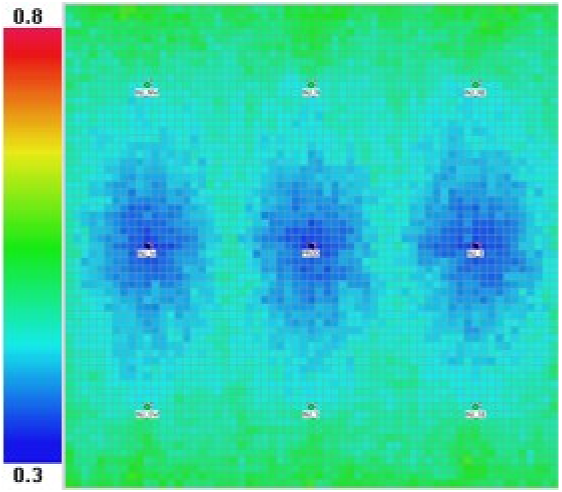

Figure 11 –Oil saturation map at latest timestep of 1-Direct Line Drive with EUR 17%

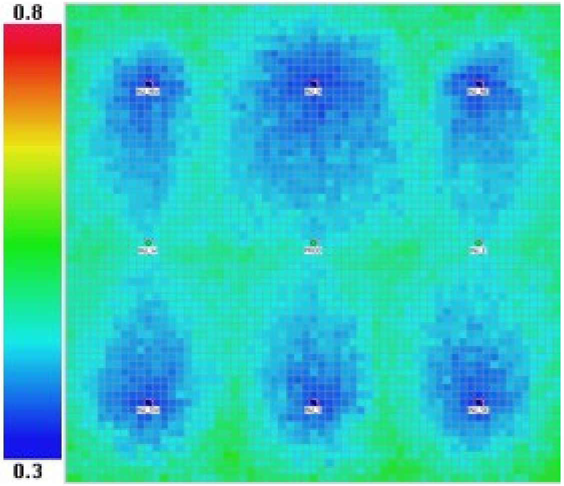

Figure 12 –Oil saturation map at latest timestep of 2-Direct Line Drive with EUR 15%

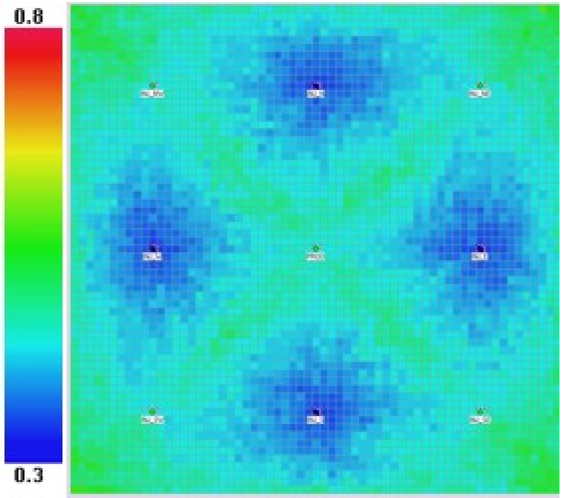

Figure 13 –Oil saturation map at latest timestep of 5-spot pattern with EUR 17%

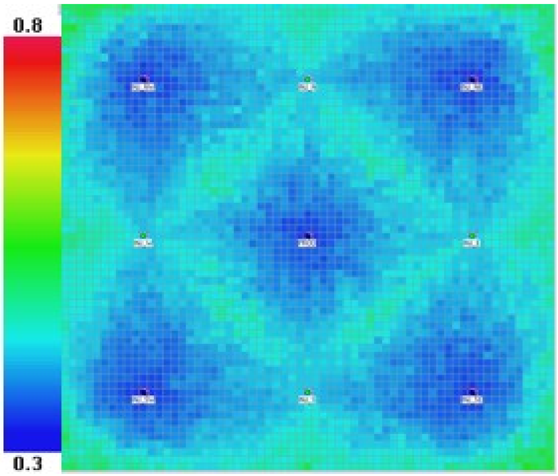

Figure 14 – Oil saturation map at latest timestep of Inverted 5-spot pattern with EUR 21%

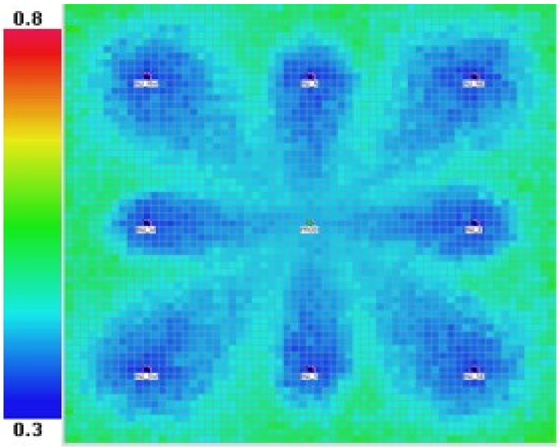

Figure 15 –Oil saturation map at latest timestep of 9-spot pattern with EUR 18%

Concluding Remarks

The proposed innovative workflow and modeling approach can identify a potential improve oil recovery using waterflooding in challenging situation such as complex reservoir geology, depleted and dipping reservoir and completed with commingled production. This approach can successfully explain the mechanism how reservoir was being produced and why oil recovery has low oil recovery due to poor reservoir management. It is also noticed that engineers should conduct comprehensive evaluation of available data to be a value.

References

A. B. Dyes, 1954, Production of Water-Driven Reservoirs below their Bubble Point, One Petro SPE 417-G, J. Petrol Technol. **6**, 31.