A PROXY MODEL TO PREDICT WATERFLOODING PERFORMANCE IN CHANNELING DELTAIC SAND RESERVOIR

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ABSTRACT

In recent days, waterflooding activities carried out as a part of secondary recovery. Before performing waterflooding, engineers have to perform reservoir simulation first to predict reservoir performance in order to waterflood. Generally, reservoir simulation is conducted by using numerical simulation method. Numerical simulation gives precise results although it depends on the availability, quality, and quantity of reservoir characteristic and injection operation data. In addition, numerical simulation also time-consuming and quite complex to use. Proxy model is kind of machine learning. It’s able to predict performance of waterflooding quickly and easier to use. The result isn’t differ too much with numerical simulation method. Proxy model is an equation model that construct form quite many experiment data. This research is trying to predict performance of normal 5 spot waterflooding in reservoir with channeling deltaic sand sedimentation by using proxy model. The proxy model will be tested on a real field case. The results indicate that proxy model is able, faster, reliable and easy to use to predict waterflooding performance in such type of reservoir.

Keywords: Proxy Model; Waterflooding; Deltaic Sedimentation

INTRODUCTION

Waterflooding is an injection process of water into reservoir formation with purposes to increase reservoir pressure and sweep oil to producer well. The goal is to enhance oil recovery.

Several issues that need to pay attention are water allocate, optimum water production rate, optimize complesion zone for producer and injector well, determine injection pattern, and determine production and injector well number to get number of oil we need.

Numeric simulation is an approachment by doing reservoir characteristic modelling to evaluate reservoir performance. This method can predict oil production rate in waterflooding process. Meanwhile, this method needs good and complete data, takes times, and quite complex.

Proxy model is a predictive model that can predict reservoir performance more faster and easy to use than reservoir simulation. This is also called surrogate model or reponse surface. A model that can optimize and do somework more efficient. Proxy model have been developed in petroleum engineering since earlier 1993 as shown in table 1.

This project try to build a proxy model to evaluate waterflooding performance in easiest way, efficient, less time consuming, and reliable for normal 5-spot waterflooding in deltaic channel bedded sand sedimentation.

METHODOLOGY

a. Data

Data that used here come from assumptions for vary reservoir condition. Bellow are sample data range:

- Fluid reservoir data vary between 30lbm/cu-ft till 62.3 lbm/cu-ft.
- Reservoir characteristics consist of porosity, lateral permeability, and vertical permeability are contained in channel type variable. Porosity number vary between 0.1 to 0.24. Permeability are varied based on correlation between porosity and permeability. All data is defined in channel type dataset. There are 17 dataset exclude base model.
- Reservoir condition i.e. reservoir pressure, temp, thickness and depth are
taken from SPE Solution Project Model 1.

- Rock and fluid interaction i.e. relative permeability and other parameter affected is taken from SPE Solution Project Model 1.
- Reservoir dimension will be varied.
- Injection rate, injection pressure, production rate and production well pressure will be varied.
- Production time/simulation time is obtained based on estimation of ultimate recovery (with constraint max $Sw < 0.99$)

b. Methodology

This project divide into 2 part. Firstly, construct proxy model and validation. Secondly, testing the constructed proxy model.

c. Workflow

i. Proxy Model

Reservoir model will be constructed based on prepared data. Model will be built using software CMG-Builder-CMOST. After that, doing some parametrization to define input variable and input sample range data. Sensitivity analysis is the second steps after variable have been defined and ranged. After that, CMOST will create many experiment set data. In this project, Latin Hypercube Design was chosen to build experiment data. The reason because LHD is a space filling design, simple, and more efficient.

$$P_{LHS} = \frac{1}{N} \sum_{i=1}^{N} \Phi(x_i) \geq T \quad (4)$$

LHD will generate dataset. From dataset, there will result interpolation model and we called it response. This response is Proxy Model. Resulted proxy model consist of 3 kinds there are Linear Polynomial Regression Model, Simple Quadratic Polynomial Regression Model, and Reduced Quadratic Polynomial Regression Model. Proxy model selected by it’s $R^2$ and plot cumulative production oil result between proxy model and reservoir simulator. Model is good if it has $R^2$ higher than 85% and moreover the data point inside 45-90% degree curvature. Look at figure 6 bellow.

After proxy model is constructed and selected, next step is validation. Validation is done by doing input proxy model parameter sensitivity analysis. This is to make sure proxy model work in accordance with sense of petroleum engineering.

![Diagram of Proxy Model Workflow](image)

**Figure 1. Proxy Model Workflow**

ii. Proxy Model Test

Proxy model will be validate with production data of tested reservoir. Reservoir and injection parameter will be inputted into reservoir simulation software (CMG-Builder) to get number of cumulative oil production. The same data also inputted into proxy model as a input parameter and run to get the result. Later cumulative oil production resulted form reservoir simulator will be compared with proxy model.
Figure 2. Proxy Model Test Workflow

CASE STUDY

Reservoir Base Model

Reservoir model that will be used is cartesian grid with number of grid I=13, J=13, and K=5 as seen in figure 8 bellow. Model is a normal 5 spot pattern.

Figure 3. Base Model

Reservoir has 7500 ft in depth with thickness 3 ft each layer, 7000 ft in GOC and 9500 ft in WOC. Porosity and permeability number of each layer different as seen in table 2 and accordance with porosity and permeability correlation by table 3 data. Look at figure 9.

- Running time
  Liquid production rate are sensitized from minimum number 100 bbl/d until maximum number 3000 bbl/d. The purpose is to get the maximum number of running time. This part can be seen in figure 18 at list of figure section.

Table 1. Porosity of Base Model

| Depth (ft) | Porosity (fraction) |
|-----------|---------------------|
| 7500      | 0.1996              |
| 7503      | 0.2037              |
| 7506      | 0.2071              |
| 7509      | 0.2085              |
| 7512      | 0.2126              |
| 7515      | 0.216               |

Figure 4. Porosity vs Permeability Plot

Table 2. Porosity and Permeability Correlation

| Porosity (fraction) | Lateral Permeability (mD) | Vertical Permeability (mD) |
|---------------------|----------------------------|-----------------------------|
| 0.1996              | 200                        | 75                          |
| 0.2037              | 244                        | 97                          |
| 0.2071              | 288                        | 119                         |
| 0.2085              | 308                        | 129                         |
| 0.2126              | 377                        | 166                         |
| 0.216               | 445                        | 204                         |
| 0.2174              | 476                        | 223                         |
| 0.2215              | 582                        | 286                         |
| 0.2249              | 687                        | 352                         |
| 0.2264              | 736                        | 383                         |
| 0.2304              | 898                        | 492                         |
| 0.2338              | 1060                       | 805                         |
b. Reservoir Fluids

Reservoir fluid is a black oil with API 59. Table 4 show data that used to construct relative permeability between oil and water in figure 10.

![Figure 5. Relative Permeability Water and Oil](image)

| Sw (fraction) | Krw (fraction) | Krow (fraction) |
|---------------|----------------|-----------------|
| 0.2           | 0.000244       | 0.823975        |
| 0.275         | 0.001953       | 0.669922        |
| 0.3125        | 0.006592       | 0.536377        |
| 0.35          | 0.015625       | 0.421875        |
| 0.3875        | 0.030976       | 0.32499         |
| 0.425         | 0.052734       | 0.244141        |
| 0.4625        | 0.08374        | 0.177979        |
| 0.5           | 0.125          | 0.125           |
| 0.5375        | 0.177979       | 0.08374         |
| 0.575         | 0.244141       | 0.052734        |
| 0.6125        | 0.32499        | 0.030976        |
| 0.65          | 0.421875       | 0.015625        |
| 0.6875        | 0.536377       | 0.006592        |
| 0.725         | 0.669922       | 0.001953        |
| 0.7625        | 0.823975       | 0.000244        |

Meanwhile PVT data shown in table 5 (SPE Solution Project Model 1).

| Parameter | Explanation          | Unit   | Min   | Max   |
|-----------|----------------------|--------|-------|-------|
| Rs        | Oil density          | lbm/cu- | 30    | 62.3  |
| Bo        |                      | ft     |       |       |
| Eg        |                      |        |       |       |
| Visc.oil  |                      |        |       |       |
| Visc.gas  |                      |        |       |       |
| P          |                       |        |       |       |
| Rs         |                       |        |       |       |
| Bo         |                       |        |       |       |
| Eg         |                       |        |       |       |
| Visc.oil  |                       |        |       |       |
| Visc.gas  |                       |        |       |       |

![Table 3. Relative Permeability Data](image)

Table 4. PVT Data

| Parameter | Explanation | Unit   | Min   | Max   |
|-----------|-------------|--------|-------|-------|
| H_layer   | Thickness   | ft     | 15    | 100   |
| REFDEPTH  | Depth       | ft     | 1000  |       |
| STW       | Injection Rate | STB/D | 100  | 12500 |
| STL       | Production Rate | STB/D | 100  | 3000  |
| BHP_prod  | Production Well BHP | psia  | 50   | 250   |
| BHP_injection | Injection Well BHP | psia  | 0.7*Depth | |
| REFPRESS  | Pressure     | psia   | 0.433*Depth | |
| SW        | Water Saturation | fraction | 0.05 | 0.25  |
Value of porosity and permeability have been collected accordance to porosity permeability correlation. Determining the prefer channel type is based on gradien number of porosity vs layer number.

d. Proxy Model Test

In this part, proxy model will be tested to predict cumulative oil production of such waterflooded reservoir. Reservoir is a conceptual model that come from paper title “Sensitivity of Waterflooding Operating Parameter, Applied to Typical Deltaic Depositional Bedded-Facies Sands; A conceptual Simulation Study” written by Siswoyo (2012). Model can be seen in figure 11 bellow.

![Tested Reservoir Model](image)

Figure 6. Tested Reservoir Model

Model is cartesian grid with number of grid I=25, j=25, K=20. Grid size are 54 ft in X,Y direction and i ft in K direction. Injection pattern is normal 5 spot with 2000 ft in depth and i ft thickness for each layer. Oil water contact is 2020 ft.

Tested reservoir’s data are shown in table 7 and 8 bellow. Table 7 is input parameter that will be used in proxy model. Meanwhile table 8 is the value of porosity and permeability for each layer.

| Channel_type | 8 |
|--------------|---|
| AREA (ft²)   | 1822500 |
| Oil_dens (lbn/cuft) | 52.6849 |

Gradien of porosity and reservoir layer is 336.7 as shown in figure 12. Based on dataset, the nearest gradien number to 336.7 is dataset 8 i.e. 220.33. Then input parameter for channel type is 8.

| Table 6. Tested Reservoir Data |
|----------------|
| Channel_type | 8 |
| AREA (ft²)   | 1822500 |
| Oil_dens (lbn/cuft) | 52.6849 |

| Table 7. Porosity and Permeability Number |
|----------------|
| Layer | Porosity (fraction) | Lateral Permeability (mD) | Vertical Permeability (mD) |
|---|----------------|----------------|----------------|
| 1 | 0.1996 | 200 | 75 |
| 2 | 0.2037 | 244 | 97 |
| 3 | 0.2071 | 288 | 119 |
| 4 | 0.2085 | 308 | 129 |
| 5 | 0.2126 | 377 | 166 |
| 6 | 0.216  | 445 | 204 |
| 7 | 0.2174 | 476 | 223 |
| 8 | 0.2215 | 582 | 286 |
| 9 | 0.2249 | 687 | 352 |
| 10 | 0.2264 | 736 | 383 |
| 11 | 0.2304 | 898 | 492 |
| 12 | 0.2338 | 1060 | 805 |
| 13 | 0.2353 | 1138 | 661 |
| 14 | 0.2393 | 1385 | 845 |
| 15 | 0.2427 | 1632 | 1037 |
| 16 | 0.2442 | 1758 | 1138 |
| 17 | 0.2481 | 2126 | 1444 |
| 18 | 0.2514 | 2494 | 1762 |
| 19 | 0.2531 | 2716 | 1961 |
| 20 | 0.2567 | 3230 | 2435 |
RESULT AND DISCUSSION

1. Proxy Model

CMOST generate many experiment data and train those data to create interpolation model called response. This response is proxy model.

There are 3 kinds of Polynomial Regression proxy model constructed by CMOST, there are:

a. Linear type Polynomial Regression Model
b. Simple quadratic type Polynomial Regression Model
c. Quadratic type Polynomial Regression Model

a) Linear Type Polynomial Regression Model

This type gives a bad result, with $R^2$ 74.6% and moreover many data point outside 45-90% degree confidence line. The plot can be seen in figure 13 bellow.

b) Simple Quadratic Polynomial Regression Model

This type gives a bad result with $R^2$ slightly improve 76.38% . Many data also point outside 45-90% confidence curve as seen in figure 14 here.

c) Quadratic type Polynomial Regression Model

This type gives the best result. $R^2$ is 85.34% and data point inside 45-90% confidence curve made a trend as seen in figure 15 here.

Based on those type, Quadratic type Polynomial Regression Models are choosen as proxy model in this project. Proxy Model equation is constructed by several parameter, there are:

i. Heterogenity degree of porosity and permeability (channel type)
ii. Area of reservoir
iii. Reservoir thickness
iv. Oil density
v. Reservoir depth
vi. Injection rate
vii. Production rate
viii. Water saturation
ix. Water viscosity, and  

x. Bottom hole pressure of producer well

a. Sensitivity Analysis

Using sobol analyze method, reservoir and injection parameter that impact oil production much can be known. From figure 16 shows that 88.8% oil production is affected by area, thickness and production rate.

Beside those parameter mention before, others like reservoir depth, injection pressure, reservoir characteristics, injection rate, BHP producer well, water viscosity, oil density and water saturation also affect oil production number.

| BHP prod (psi) | Np oil (STB) |
|----------------|-------------|
| 50             | 740119.34   |
| 100            | 728947.52   |
| 150            | 717775.71   |
| 200            | 706603.89   |
| 250            | 695432.07   |

ii. Reservoir Area

Based on sample data, proxy model is made for area vary between 6806.25 ft² to 1847580 ft². If area of reservoir larger, then number of reserve will be higher too. This statement have been proved by proxy model in table 10 below.

| Area (ft²) | Cum_Oil_Prod_Proxy (STB) |
|------------|--------------------------|
| 6806.25    | 27299.8496               |
| 1847580    | 894706.9764              |

iii. Reservoir thickness

If thickness of reservoir getting higher, then reserve will be higher too. According to sample data, thickness reservoir vary between 15 ft to 100 ft. Proxy model on table 11 show that thickest reservoir thickness 100 ft resulting the more oil.

| H(ft) | Cum_Oil_Prod_Proxy (STB) |
|-------|--------------------------|
| 15    | 258351.9949              |
| 100   | 1318943.631              |

iv. Oil Density

If oil is getting lighter, then it will be more easier to flow. This statement accordance with proxy model testing, where the lightest oil gives more oil production. Look at table 12 below.

| Oildens (lbm/cuft) | Cum_Oil_Prod_Proxy (STB) |
|--------------------|--------------------------|
| 30                 | 915490.9994              |
| 62.3               | 901374.6736              |

Figure 11. Effect of Reservoir and Injection Parameter

After proxy model is obtained, proxy need to validate by doing sensitivity analysis to input parameters. Goal is known proxy model work properly accordance with petroleum engineering sense.

i. BHP Produksi

Based on sample data, bottom hole pressure of producer well vary between 50 to 250 psia. Higher number of producer bottomhole pressure, there lower oil production as BHP act like a resistant to flow. Proxy model in table 9 show this phenomenon by calculating cumulative oil production for each incremental pressure while other parameter constant.
v. Reservoir Depth
A deeper reservoir will be more harder to be produced than not. Vice versa. In table 13 bellow proxy model make prediction of different depth of reservoir (max and min) and resulting maximum oil production in shallow reservoir.

### Table 12. Sensitivity of Reservoir Depth

| REFDEPTH (ft) | Cum_Oil_Prod_Proxy (STB) |
|---------------|--------------------------|
| 1000          | 953976.0099              |
| 10000         | 824240.6598              |

vi. Water Injection Rate
Injected water function as piston like tool to push and sweep oil toward producer well. In table 14 proxy model show effect of water injection rate to oil production. The higher number of injection rate, the higher number of oil production too.

### Table 13. Sensitivity of Injection Rate

| Injection Rate (STB/D) | Cum_Oil_Prod_Proxy (STB) |
|------------------------|--------------------------|
| 100                    | 842855.1553              |
| 12500                  | 900468.2899              |

vii. Production Rate
If liquid production rate is higher, cumulative oil production will be higher too. As seen in table 15, the maximum liquid production rate gives higher oil production in cumulative than minimum production rate.

### Table 14. Sensitivity of Production Rate

| Production Rate (STB/D) | Cum_Oil_Prod_Proxy (STB) |
|-------------------------|--------------------------|
| 100                     | 612930.1212              |
| 3000                    | 918176.4283              |

viii. Water Saturation
If water saturation is getting lower, then the number of oil saturation will be higher. Vice versa. This means oil reserve is higher then oil production will be higher too. Proxy model in table 16 show the prediction of cumulative oil production for maximum and minimum water saturation.

### Table 15. Sensitivity of Water Saturation

| SW (fraksi) | Cum_Oil_Prod_Proxy (STB) |
|-------------|--------------------------|
| 0.05        | 900468.3                 |
| 0.25        | 898593.9                 |

ix. Water Viscosity
Water in this term refer to reservoir fluid not injected water or called VWI. The viscous water will be more difficult to move than not. Oil will be more moveable then oil production will be getting higher as seen in table 17 bellow.

### Table 16. Sensitivity of Water Viscosity

| VWI (cP) | Cum_Oil_Prod_Proxy (STB) |
|----------|--------------------------|
| 0.2325   | 879365.6                 |
| 0.3875   | 927436.4                 |

b. Proxy Model Test
Based on waterflooded reservoir accordance to reference paper, at the running time 15 years simulator result cumulative oil production approximately 586.24 MSTB. Figure 17 show the plot between cumulative oil production and time.

![Tested Reservoir Cumulative Oil Production](image12)

Field data in table 7 are inputted as input variable/parameter in Quadratic type Polynomial Regression Model. Proxy model gives the cumulative oil production about 251.8422 MSTB.
Comparing cumulative oil production between reservoir simulator and proxy model produce about 57.04% relative error. This error is quite big. There are several reason that could make this happen.

Firstly, inability of channel type to represent reservoir characteristics (por, lateral and vertical permeability) of tested reservoir. Channel type are just determined by 17 dataset. Determining appropriate channel type is based on the nearest predicted reservoir gradient number of porosity vs layer. In this case, tested reservoir gradient number is 336.7 while the nearest gradient number in channel type dataset is 220.33 so there is a big different.

Secondly, Quadratic type Polynomial Regression Model is constructed by 1751 experiment data. If we look at figure 16 there are several outliers point. As explained earlier, polynomial regression model is sensitive to outliers data although $R^2$ is fit about 85% higher.

Thirdly, from graphic between proxy model result and simulator result in figure 17 data point are located in 45-90 degree line from 0 until 1.2 MMSTB of cumulative oil production. Above that, data point tend to shape a new regression model.

CONCLUSION

1. Proxy model has build as seen below. Parameters are named in variable A, B, C and so on and explained in nomenclature.

\[
N_{poil} = 244525 + A \\
\times (0.00117782 \times B + 26.5296) \\
\times (J - 24599.6) + B \\
\times (0.0059722 \times C + 2.67235) \\
\times e^{-6} \times F + 0.0191376) + C \\
\times (0.0659058 \times F - 0.160888) \\
\times E + 1.0212 \times G - 444.146) - D \\
\times (0.525111 \times G + 4162.1) + E \\
\times (14.2898 - 4.10121 \times e^{-6} \times B) \\
+ F \\
\times (0.00173314 \times G - 8.33252) \\
+ G \\
\times (69.4146 + 5.4512 \times e^{-5} \times B) \\
+ H \\
\times (2.04112 \times e^{-6} \times I - 610480) \\
- I \times 200145 - J \\
\times (136.517 + 0.000130482 \times B) \\
+ 106.42 A^2 \\
- 3.48496 \times e^{-8} \times B^2 + 52.4761 \\
\times D^2 - 0.000955359 \times E^2 \\
- 0.0418242 \times G^2
\]

2. Sensitivity result in table 9 until table 17 show proxy model are valid to use in evaluating waterflood performance of deltaic channel sand sedimentation reservoir specific in normal 5-spot pattern.

3. Proxy model can predict waterflooding performance in tested reservoir with relative error 57.04% to reservoir simulator. Quadratic type Polynomial Regression Model is able to predict waterflooding performance more faster, easier, and efficient than reservoir simulator.

RECOMMENDATION

1. Reservoir characteristics such as porosity and permeability each layer limited only 17 dataset. Further, it will be better to create as many as possible channel type dataset.

2. Create minimum 900 experiment data with relative error 10% into simulator.

3. This project is limited only for normal 5-spot pattern, it’s recommended to develop into other pattern.

4. Proxy model could do optimization by giving allocated water injected and surface facilities production data.

5. For more reliable result, parameters to evaluate should be not only cumulative
production, but also recovery number (RF).

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