THE USE OF WATER FLOODING TO IMPROVE OIL RECOVERY BY USING RESERVOIR SIMULATION

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Abstract

There are 18 oilfields in the northern, central parts and Gulf of Thailand which produce an optimal production rate of 130,000 barrels per day accounting for 20% of the consumption of Thailand. It is necessary to do reservoir simulation to determine the most suitable and efficient patterns for individual water flooding projects. The objectives of this study are: 1) to compile oil reservoir data in Thailand; 2) to model oil reservoirs using “Eclipse office” software; 3) to determine oil recoveries and return on investments by various methods including primary recovery, conventional water flooding, and bottom water injection. Three sizes of oilfields were modeled with the oil in place of 109, 29, and 5.8 million barrels respectively. Many producing and injecting well patterns were modeled using Eclipse Office in DMF office to run simulations in each oil field. The oil productions in primary recovery ranged from 20 - 23% with the present profit per investment ratio (PIR) of 0.50 - 0.62 respectively. The total oil production recovery with conventional water flooding was at 35 - 39% with the PIR of 0.50 - 0.88. For bottom water injection, the total oil recovery was at 40 - 48% with the PIR of 0.53 - 1.25. The conclusion was that the bottom water injection method increased oil production and profits more than conventional water flooding and the primary recovery method.

Keywords: Water flooding, oil, recovery, improvement, simulation

Introduction

Petroleum is the most important energy source for social and economic development in Thailand. It is utilized in many sectors such as communications, industries, agriculture, and power generation, etc. Daily oil consumption in Thailand is about 800,000 barrels of which more than 700,000 barrels need to be imported while only 130,000 barrels is from indigenous production. Today, 18 oilfields are in production such as Sirikit and Bechamas oilfields, etc. Some of these oilfields have been producing oil for many years and production which used the primary recovery method has started to decline. In order to maintain or increase the production rate, some companies are using water flooding, which is called secondary recovery. Water flooding is the most preferable method to improve oil recovery because it is simple and inexpensive. Reservoir simulation is a powerful and inexpensive tool, which can predict what is going on in the reservoir and the amount of production from alternative operations.
Reservoir simulation is necessary to find the most efficient water flooding pattern for an individual project. The bottom water injection method will give the most oil recovery because it yields highest displacement efficiency due to water-oil gravity segregation. The objectives of this study are: 1) to compile oil reservoirs data in Thailand; 2) to model oil reservoirs in computer using “Eclipse office” software; 3) to determine the improvement of oil recoveries and return on investments by various methods including primary recovery, conventional water flooding, and bottom water injection.

Methodology

Laboratory Experiment and Analysis

More than 30 tertiary rock samples were collected for random analyses from many areas in the central and northern parts of Thailand. The porosity and permeability were measured at the values of 1.2 - 36.6% with an average of 17% and 0.0002 to 51.38 md (millidacies) with an average of 5.2 md. The porosity and permeability obtained from PTTEP Company are 11 - 23% and 0.1 - 500 md for the Uthong oil field and 12 - 30% and 1 - 1,000 md for Sirikit oil fields respectively.

Reservoir Simulation Model Development

Three sizes of reservoir simulation models of 109, 29, and 6 MMSTB oil in place were developed by utilizing “Eclipse Office” software. The details of each model are discussed as follows.

(1) SUT 1 Model

This model covers an area of 900 acres (39,000,000 ft²), contains 8 layers, 625 cells/layer, up to a total of 5,000 cells (Grid Blocks). The oil in place is about 109 MMSTB. The layers are separated by different porosity and permeability ranging from 19 - 26% and 9.2 - 586 md from the bottom to the top of the reservoir. There are 25 initial producing wells and some producing wells will turn to injection wells (IP wells) later as shown in Figure 1.

(2) SUT 2 Model

This model covers an area of 210 acres (9,000,000 ft²), contains 8 layers, 625 cells/layer, up to a total of 5,000 cells (Grid Blocks). The oil in place is about 29 MMSTB. The layers are separated by different porosity and permeability ranging from 18 - 25% and 30 - 100 md from the bottom to the top of the reservoir. There are 9 initial producing wells and some producing wells will turn to injection wells (EP wells) later as shown in Figure 2.

Figure 1. SUT 1 model
(3) SUT 3 Model

This model covers an area of 360 acres (15,681,600 ft²), contains 8 layers, 400 cells/layer, up to a total of 3,200 cells (Grid Blocks) (Figure 3). The oil in place is about 5.8 MMSTB. The layers are separated by different porosity and permeability ranging from 18 - 25% and 30 - 100 md from the bottom to the top of the reservoir. There are 6 initial producing wells (P wells) and after three years of production two water injection wells (W wells) will be added.

Reservoir Simulation Input Data

The input data for each model were collected and obtained from a review of concessionaire results, laboratory measurement, and from assumptions. Many sets of input data were input into the models, however only one set of data for SUT 1 model will be illustrated in this paper as follows.

(a) Fluid properties

°API oil gravity = 39.4°API
Solution gas gravity = 0.8

Figure 2. SUT 2 model

Figure 3. SUT 3 model
Water Flooding Simulation

Water density = 62.428 lb/cu.ft. Water compressibility @ 3,500 psi = $3.081 \times 10^{-6}$ psi$^{-1}$
Water viscosity = 0.296 cp
Oil formation volume factor = 1.055 - 1.286 bbl/STB
Solution gas oil ratio = 0.001 - 0.482 MSCF/STB
Oil viscosity = 2.1 - 6.7 cp
Gas viscosity = 0.013 - 0.024 cp
And other calculated fluid properties were obtained from built in software of Eclipse Office software.

(b) Rock properties
Porosity = 19 - 26%
Permeability = 9.2 - 586 md
$k_v = k_h$ for bottom water injection cases
$k_v = 0.1 k_h$ for conventional (edge) water injection cases

(c) Reservoir properties
Depth Oil-Water contact = 3,915 ft
Initial reservoir pressure@3,850 ft = 3,500 psia
Bubble point pressure = 1,800 psia
Reservoir temperature = 203°F
The relative permeability is generated by Eclipse.

Simulation Patterns

Many producing and injecting wells patterns were run for each model as follows.

(a) SUT 1 Model (109 MMSTB oil in place)
Pattern 1: There are 25 oil producing wells for 25 years of production (only primary recovery).
Pattern 2: There are 25 oil producing wells initially and later 8 wells will be converted to water injection wells (Figure 1).
Pattern 3: There are 25 oil producing wells initially and later 9 wells will be converted to water injection wells.

(b) SUT 2 Model (29 MMSTB oil in place)
Pattern 1: There are 9 oil producing wells, no water injection (only primary recovery)
Pattern 2: There are 9 oil producing wells initially, then 4 wells will be converted to water injection wells (Figure 2).

(c) SUT 3 Model (5.8 MMSTB oil in place)
Pattern 1: There are 6 oil producing wells, no water injection (only primary recovery)
Pattern 2: There are 6 oil producing wells initially, then 2 water injection wells will be added after three years of production (Figure 3).

Results and Discussion

The results of some pattern simulations are listed in Table 1, and all pattern simulation results are reported in the author’s full research report.

A brief discussion follows.

1. The primary recovery methods such as SUT 1 Model LKB Noinj, SUT2 Model SP Noinj, and SUT3 SUT Noinj yielded oil recovery of 20 - 23%.

2. The early conventional (edge) water flooding (2 - 4 years after the production started) methods such as SUT 1 Model LKB Inj8 2yr, SUT 2 Model SP Inj4 4yr, and SUT 3 SUT Inj2 3yr, etc., yielded oil recovery of 35 - 39%.

3. The bottom water injection methods such as SUT 1 Model LKB Inj8 2yr BWD, SUT 2 Model SP Inj4 4yr BWD, and SUT 3 SUT Inj2 3yr BWD, etc., yielded oil recovery of 40 - 48%.

4. The oil production and water injection rates for each case resulted from trial and error to obtain the optimal recovery.

The earlier water injection is used (after starting oil production) the more oil recovery there is, because of the reservoir pressure is still high allowing more oil displacement efficiency. The time when the reservoir pressure drops close to the bubble point pressure should be the suitable injecting time. The suitable number and location of injectors will yield the optimal recovery, which can be obtained by trial and error. The bottom water flood yields most recovery due to the higher specific gravity of water than oil displacing from the bottom yields higher displacement efficiency. Two sets of simulation results are illustrated below namely SUT 1 Model Pattern LKB Noinj and SUT 1 Model Pattern Model LKB Inj8 2yr BWD.

**SUT 1 Model Pattern 1** (No water injection). The following graphs show...
a. Fluid production rate vs. Time plot (Figure 4)
   b. Cumulative fluid production vs. Time plot (Figure 5)

The oil production rate was maintained at the rate of 10,000 barrels/day for four years then declined and ended at the rate of 308 barrels/day (Figure 4).

The cumulative oil production is 25.4 million barrels at the end of the 25th year of production with the recovery of 23.3% of original oil in place (Figure 5).

**SUT 1: Model Pattern 2.1b** (LKU Inj8 2yr BWD Bottom water flooding injection started at

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### Table 1. A summary of the simulation results

<table>
<thead>
<tr>
<th>Model</th>
<th>Pattern</th>
<th>Water flooding style</th>
<th>Number of oil producing wells before/after water injection</th>
<th>Number of water injecting wells</th>
<th>Year of starting water injection</th>
<th>Total oil production (barrels)</th>
<th>Oil recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LKB Noijn</td>
<td></td>
<td></td>
<td>25/25</td>
<td>0</td>
<td>25,438,270</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 2yr</td>
<td>Conventional</td>
<td></td>
<td>25/17</td>
<td>8</td>
<td>42,911,256</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>SUT 1</td>
<td>LKB Inj8 2yr BWD</td>
<td>Bottom</td>
<td>25/17</td>
<td>8</td>
<td>52,563,296</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>LKB Inj8 4yr</td>
<td>Conventional</td>
<td>25/17</td>
<td>8</td>
<td>41,981,916</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>109 mmstb</td>
<td>LKB Inj8 4yr BWD</td>
<td>Bottom</td>
<td>25/17</td>
<td>8</td>
<td>52,503,728</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Oil in place</td>
<td>LKB Inj8 8yr</td>
<td>Conventional</td>
<td>25/17</td>
<td>8</td>
<td>38,664,156</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 8yr BWD</td>
<td></td>
<td>Bottom</td>
<td>25/17</td>
<td>8</td>
<td>43,385,244</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>LKB Inj9 4yr BWD</td>
<td></td>
<td>Bottom</td>
<td>25/9</td>
<td>9</td>
<td>42,085,068</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>LKB Inj9 4yr BWD</td>
<td></td>
<td>Bottom</td>
<td>25/9</td>
<td>9</td>
<td>52,283,176</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>SUT 2</td>
<td>SP Noijn</td>
<td></td>
<td>9/9</td>
<td>0</td>
<td>5,725,796</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>SP Inj4 4yr</td>
<td>Conventional</td>
<td>9/5</td>
<td>4</td>
<td>10,866,865</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>59 mmstb</td>
<td>SP Inj4 4yr BWD</td>
<td>Bottom</td>
<td>9/5</td>
<td>4</td>
<td>13,670,438</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>SUT3</td>
<td>SUT Noijn</td>
<td></td>
<td>6/6</td>
<td>0</td>
<td>1,520,000</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>5.8MMSTB</td>
<td>SUT Inj2 3yr BWD</td>
<td>Bottom</td>
<td>6/6</td>
<td>2</td>
<td>3,080,000</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 4. Model pattern 1 LKB Noijn fluid production rate vs. time**
the third year of oil production in 8 injection wells). The results are shown in the following graphs.

a. Fluid production rate vs. Time plot (Figure 6)

b. Cumulative fluid production vs. Time plot (Figure 7)

The oil production rate was maintained at the rate of 7,500 barrels/day for thirteen years then declined and ended at the rate of 2,900 barrels/day (Figure 6).

The cumulative oil production is 52.6 million barrels at the end of the 25th year of production with the recovery of 48.2% of original oil in place (Figure 7).

**Economic Analysis**

The objective of an economic analysis is to study the commerciality of each pattern which
results from reservoir simulation. The analysis includes:

1. Cash flow in-out
2. Internal rate of return (IRR) and net present value (NPV) of each project
3. Return on investment period (Pay out period)
4. Net profit and Taxes
5. Internal rate of return and net present profit per investment comparison

The Excel program was developed to carry out an economic analysis based on the following regulations and assumptions:

- Oil price 80 US$/STB
- **Capital investment**
  1. Concession application
     - Big reservoir 150 MMB
     - Medium 100 MMB
  2. Geological & Geophysical Exploration
     - Big size 200 MMB
     - Medium size 150 MMB
  3. Exploratory and Appraisal wells
     - Big size 420 MMB
     - Medium size 240 MMB
  4. Production wells
     - Big size 60 MMB/well
     - Small-Medium 40 MMB/well
  5. Production Facilities
     - Big size 10000 MMB
     - Medium size 2000 MMB
  6. Production Cost 600 B/STB (Lifting Cost)
  7. Water Injection Cost
     - Facilities 2 MMB/well
     - Well Completion & Conversion 0.2 MMB/well
     - Facility Maintenance
       - Big size 2.4 MMB/year
       - Small size 1.2 MMB/year
  8. Water Injection Cost 10 B/bbl
  9. Discounted Rate (Interest Rate) 8%
     - Escalation 2%
  10. Sliding Scale of Royalties
      - (Production Level) (Rate) (%)
      - 0 – 2,000 BPD 5.00
      - 2,000 – 5,000 BPD 6.25
      - 5,000 – 10,000 BPD 10.00
      - 10,000-20,000 BPD 12.50
      - > 20,000 BPD 15.00
  11 Income Tax 50%

Many different sized models and patterns were analyzed for a comparison of economic

![Figure 7. Model pattern 2 LKU Inj8 2yr BWD cumulative fluid production vs. time](image)
expectations. Some examples are shown in Table 2. However, the analysis leads to the following conclusions. For primary recovery only, the internal rate of return (IRR) after tax and 8% discounted ranges between 25 - 46% with net present value profit per investment ratio of 0.50 - 0.62 from small to large oil fields. If the conventional water flooding is included, the IRR becomes 14 - 37% with net present value profit per investment ratio of 0.50 - 0.62, while the bottom water injection earns IRR of 14 - 37% with net present value profit per investment ratio of 0.53 - 1.25. The net present value profit after tax of the project including water flooding will be 1.1 - 1.8 times that of the project which is produced using only primary recovery. Some of the economic results are presented in Table 2.

**Table 2. Economic analysis summary**

<table>
<thead>
<tr>
<th>Producing Patterns</th>
<th>Total Oil production (bbl)</th>
<th>Recovery Factor</th>
<th>Profit after Income tax (8% Discount) (Million Baht)</th>
<th>Internal Rate Of Return After income tax (8% Discount)</th>
<th>PIR</th>
<th>Net present value profit per Investment ratio (8% Discount)</th>
<th>Water Injection Rate : $I_w$ (bbl/d)</th>
<th>Oil Production Rate : $Q_o$ (bbl/d)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>LKB Noinj</td>
<td>25,438,270</td>
<td>0.23</td>
<td>7,632</td>
<td>46.28%</td>
<td>0.62</td>
<td>-</td>
<td>10,000</td>
<td>10,000</td>
<td>7,500</td>
</tr>
<tr>
<td>LKB Inj8 2yr</td>
<td>42,911,256</td>
<td>0.39</td>
<td>10,768</td>
<td>36.24%</td>
<td>0.88</td>
<td>10,000</td>
<td>7,500</td>
<td>7,500</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 2yr BWD</td>
<td>52,563,296</td>
<td>0.48</td>
<td>12,601</td>
<td>36.91%</td>
<td>1.03</td>
<td>10,000</td>
<td>7,500</td>
<td>7,500</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 4yr</td>
<td>41,981,916</td>
<td>0.38</td>
<td>9,390</td>
<td>28.53%</td>
<td>0.77</td>
<td>10,000</td>
<td>6,250</td>
<td>6,250</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 4yr BWD</td>
<td>52,503,728</td>
<td>0.48</td>
<td>10,595</td>
<td>28.59%</td>
<td>0.86</td>
<td>10,000</td>
<td>6,250</td>
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<tr>
<td>LKB Inj8 8yr</td>
<td>38,664,156</td>
<td>0.35</td>
<td>6,136</td>
<td>13.54%</td>
<td>0.50</td>
<td>10,000</td>
<td>3,750</td>
<td>3,750</td>
<td></td>
</tr>
<tr>
<td>LKB Inj8 8yr BWD</td>
<td>43,385,244</td>
<td>0.40</td>
<td>6,472</td>
<td>13.53%</td>
<td>0.53</td>
<td>10,000</td>
<td>3,750</td>
<td>3,750</td>
<td></td>
</tr>
<tr>
<td>LKB Inj9 4yr</td>
<td>42,085,068</td>
<td>0.39</td>
<td>7,366</td>
<td>26.59%</td>
<td>0.60</td>
<td>10,000</td>
<td>6,250</td>
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<td></td>
</tr>
<tr>
<td>LKB Inj9 4yr BWD</td>
<td>52,283,176</td>
<td>0.48</td>
<td>8,259</td>
<td>26.74%</td>
<td>0.67</td>
<td>10,000</td>
<td>6,250</td>
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<tr>
<td>SP Noinj</td>
<td>5,725,796</td>
<td>0.20</td>
<td>1,502</td>
<td>33.80%</td>
<td>0.50</td>
<td>-</td>
<td>3,950</td>
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<tr>
<td>SP Inj4 4yr</td>
<td>10,866,865</td>
<td>0.37</td>
<td>2,486</td>
<td>33.56%</td>
<td>0.82</td>
<td>3,200</td>
<td>3,950</td>
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<td>SP Inj4 4yr BWD</td>
<td>13,670,438</td>
<td>0.47</td>
<td>2,697</td>
<td>28.09%</td>
<td>0.89</td>
<td>3,200</td>
<td>3,950</td>
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<td>SUT Noinj</td>
<td>1,520,000</td>
<td>0.22</td>
<td>547</td>
<td>24.87%</td>
<td>0.54</td>
<td>-</td>
<td>1,200</td>
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<tr>
<td>SUT Inj2 3yr</td>
<td>3,080,000</td>
<td>0.45</td>
<td>1,273</td>
<td>35.33%</td>
<td>1.25</td>
<td>1,500-1,200</td>
<td>1,200</td>
<td>1,200</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions

Reservoir simulation is a powerful tool to predict reservoir performance in many operational options, especially in water flooding projects. The most efficient and suitable water flooding pattern for individual projects can be achieved by reservoir simulation. In this study, the oil recovery from primary recovery only ranged from small to large oil fields with a size of 20 - 23% of the size of the original oil in place, when including water flooding the oil recovery increased to 35 - 48%. The bottom water flood yields most recovery due to the higher specific gravity of water yields higher oil displacement efficiency by displacing up from the bottom. The earlier water injection is used (after starting oil production) the more oil recovery there is, because of the reservoir pressure is still high allowing more oil displacement efficiency. The internal rate of return of the water flooding project seems to be less compared to the primary oil recovery alone, but the net present value profit and net present value profit/investment ratio will be higher in water injection projects. When primary production has been underway for some time, converting suitable producing wells to water injection wells at a suitable time might cost less money and earn considerable profits. More studies are needed using trial and error to get the best fit for individual water flooding projects.
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References


Harpole, K.J. (1980). Improved reservoir characterization - A key to future reservoir management for the West Seminole San Andres Unit. JPT., 32: 2,009-2,019.


