CHAPTER III
METHODOLOGY

In order to simulation waterflooding, carbon dioxide flooding and water-alternating-carbon dioxide in heavy oil reservoir, experimental procedure and experimental data needed to be collected. Softwares, experimental data, experimental procedure, simulation model and simulation steps will be presented.

The current work dealt with creating a simulation model and used input data from experimental data obtained from the previous research (Torabi *et al.*, 2010). The oil recovery techniques are focused on this work mainly divided into three techniques

1) Water flooding
2) Carbon dioxide flooding
3) Water-alternating-carbon dioxide

3.1 Softwares

The following list is all softwares that are used forthe simulation.

1. IMEX CMG (Implicit-Explicit Black Oil Simulation)
2. Builder CMG (Pre-Processing Modules)
3. Result CMG (3D, Graph & Report)
4. Microsoft Excel

3.2 Experimental Procedure

The operating condition and experimental procedure used in this simulation were the same condition as the previous experimental. All of the previous experiments were constantly operated at 25 °C and 345 kPa. The experimental procedure the water and gas were injected from one side of the sand pack and oil was produced from the other side.

3.2.1 Waterflooding

In order to perform waterflooding, a total of 4.5 pore volume of water was injected into the sand pack. The injection rate was change from 0.112 to 1.1124 cc/min and then to 5.62 cc/min after each 1.5 pore volume.

3.2.2 Carbon Dioxide Flooding

Carbon dioxide was injected into the sand pack. The injection rate of carbon dioxide was kept constantly at 1 cc/min until reached 4.5 pore volume.

3.2.3 Water-Alternating-Carbon Dioxide

4 mL of water was first injected into the sand pack with the injection rate of 1 cc/min. After that water was stopped and 4mL of carbon dioxide was injected at the same rate into the sand pack. The above procedure was repeated until nearly 4.5 pore volume for processes that used 1:1 carbon dioxide/water slug ratio. For the process that used 1:2 and 2:1 carbon dioxide/water slug ratios were repeated until reach 2.5 pore volume.

3.3 Experimental Data

The oil viscosity and sand pack permeability that were used in this simulation work were the same value as the previous experiment. Two types of oil with viscosity of 440 cp and 1500 cp were used and two different sand pack permeability were used to obtain the varying permabilities ranging from 11 to 43 darcy.

3.3.1 Core Dimensions

During the laboratory experiment is used two different cores. Each core had unique dimensions and produced different weight and pore volumes. Table 3.1 shows the respective dimensions.
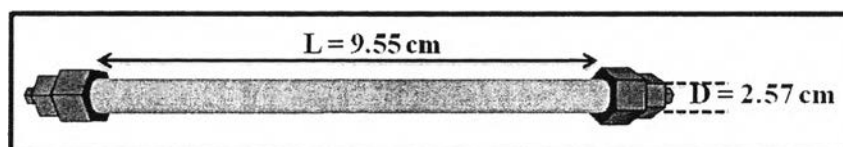

Figure 3.1 Core flooding.

Table 3.1 Core Dimensions

Dimensions	Core Flooding
Length (cm)	9.55
Diameter (cm)	2.57
Area (cm^2)	5.18
Volume (cm^3)	49.47

From the inner dimension (D) and the length of the core (L) can calculate the bulk volume:

$$BV = \pi r^2 L \qquad (3.1)$$

3.3.2 Experimental Data

Oil property, core properties, measured properties and result were collected from 11 the experiments. Test 1 and test 2 were used to compare the effect of oil viscosity in waterflooding method. Test 2 and test 3 were used to compare the effect of sand pack permeability in waterflooding method. Test 4 and test 5 were used to compare the effect of oil viscosity in carbon dioxide flooding. Test 4 and test 6 were used to compare the effect of sand pack permeability in carbon dioxide flooding. Test 7 and test 8 were used to compare the effect of oil viscosity in water-alternating-carbon dioxide. Test 8 and test 9 were used to compare the effect of sand pack

permeability. Test 8, test10 and test 11 were used to compare the effect of carbon dioxide/ water slug ratio.

Table 3.2 Experimental data(Torabi et al., 2010).

Test	Method	Oil properties	Core properties			Measured properties			Results
		μ_o (cp)	Permeability (Darcy)	PVs (cm^3)	Porosity (%)	S_{wc} (%)	S_{oi} (%)	S_{or} (%)	Recovery Factor
1	Waterflood	440	39.90	17.41	36.44	8.07	91.93	37.78	58.91
2	Waterflood	1500	38.60	18.40	38.53	12.50	87.50	41.71	52.33
3	Waterflood	1500	11.40	19.40	40.61	5.13	94.87	44.73	52.85
4	CO$_2$ flood	1500	41.51	17.41	36.44	16.12	83.88	43.23	48.46
5	CO$_2$ flood	440	38.60	18.40	38.53	26.09	73.91	53.12	28.13
6	CO$_2$ flood	1500	11.40	19.40	40.61	20.60	79.40	59.11	25.55
7	WAG(1:1)	440	43.00	18.40	36.10	2.18	97.82	51.49	47.36
8	WAG(1:1)	1500	40.60	17.41	36.44	3.48	96.52	57.88	40.02
9	WAG(1:1)	1500	12.60	19.40	40.61	0.49	99.51	59.94	39.77
10	WAG(1:2)	1500	41.95	20.39	40.01	10.74	89.26	66.57	25.41
11	WAG(2:1)	1500	42.76	19.40	38.05	13.12	86.88	65.09	25.07

3.4 CalculatingAPI Gravity

In order to create API gravity for input into the builder CMG, we used the empirical correlation equation for dead oil. The following equation was used for calculating the API gravity ranging from 10 to 22.3 (heavy oil). By using the dead oil viscosity (μ_{od}) and temperature (T).

$$\mu_{od} = 10^{(-0.71523API + 22.13766)} T^{(0.269024API - 8.268047)} \qquad (2)$$

Where μ_{od} is dead oil viscosity in mPa•s

T is temperature in °F

API is API gravity

The oil viscosity of 440 mPa•s, with temperature 77 °F gave the API gravity of 19. The oil viscosity of 1500 mPa•s, with temperature 77 °F gave the API gravity of 16.

3.5 Reservoir Model Simulation

The reservoir models were simulated with the data and procedure based on the experiments. Grid blocks model and simulation steps will be presented in this section.

3.5.1 Grid blocks model

Since this program is designed for a vertical cylindrical shape which cannot be used to replace horizontal cylindrical shape in the previous experiment due to the gravity force. Thus, this simulation work has to modify this program in order to model the horizontal cylindrical shape by using hybrid option instead of regular Cartesian grid block for improving the accuracy of results.

A Cartesian grid block has been applied for the simulation model which consisted of only one block which the same size dimensions as core dimension data. The radial of physical was converted to the equivalent rectangular area. The sand packs were considered to be homogeneous porous media. For all grid blocks were assumed to be constant porosity and permeability.In order to improve simulation

results, hybrid option was used to refine the grid block. The hybrid option was refined by using 4 grids in θ-direction, 10 grids in r-direction and 40 grids in j-direction. The refinement simulation model consisted of 1600 grid blocks. Figure 3.2 through Figure 3.4 show the refines model in hybridization in cross section area view, side view and three dimension views, respectively.
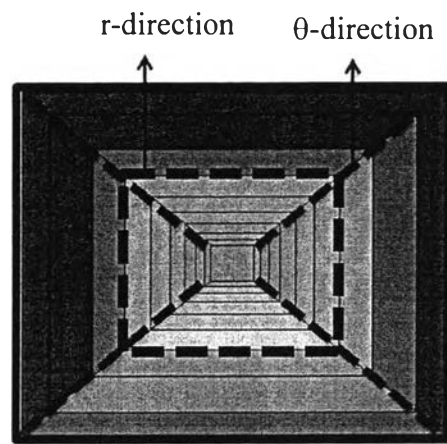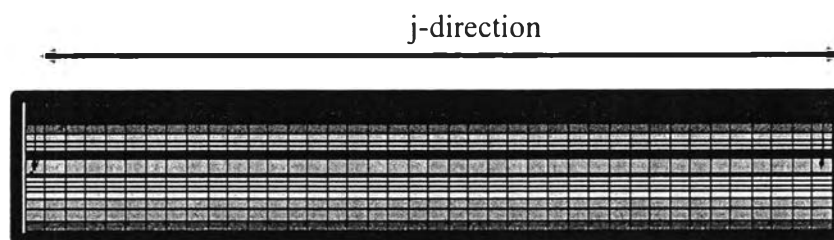

Figure3.2 Cross section area view of core model.

Figure 3.3 Side view of core model.

Figure 3.4 Three dimension views of core model.

From the experimental procedure the water and gas were injected from one side of the sand pack and oil was produce from the other side. Thus, one producer and one injector were consider perforated for simulation model at blocks (1,1,1/1,1,1/1,1,1) as a producer and (1,1,1/1,10,1/1,1,4) as an injector. The producder in experiments had well constraint of minimum bottom hole pressure of 200 kPa. Figure 3.5 show perforated location of injector and producer.
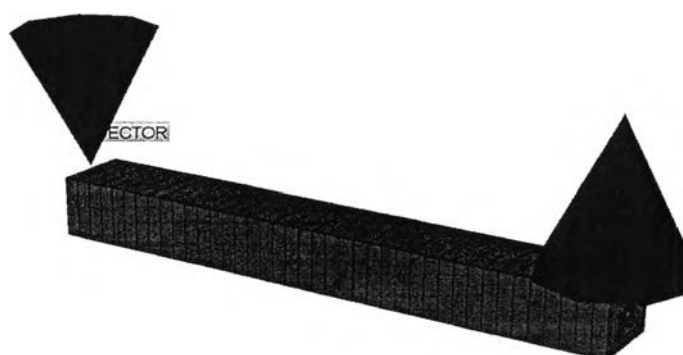

Figure 3.5 The perforated location in simulation model.

3.5.2 Simulation steps of three recovery methods

Figure 3.6 presents simulation steps in three recovery methods. It starts with waterflooding and follows by carbon dioxide flooding and water-alternating- carbon dioxide, respectively.
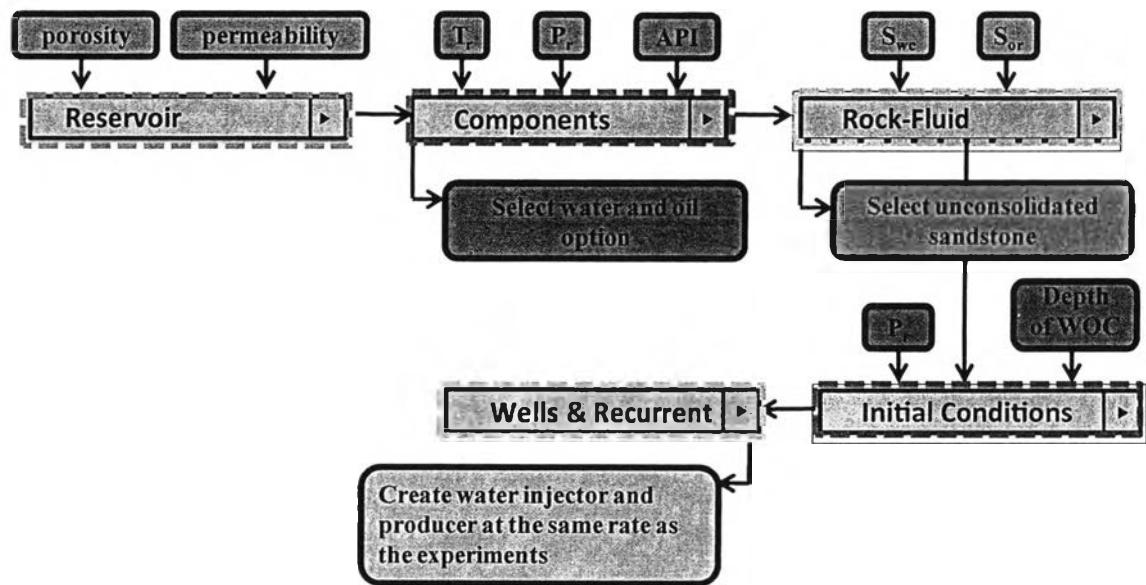
3.5.2.1 Waterflooding

Figure 3.6 Schematic diagram of simulation steps in waterflooding.

From a schematic diagram of water flooding (Figure 3.6), A Cartesian grid is created in a reservoir using I-, J-, and K- directions equal to 1 and selecting block widths equals to 0.0257 meters and 0.0955 meters for I- and J-direction, respectively. The grids are then edited by refining the current fundamental layer using 10 in the block of j-direction for refinement j-direction. The hybrid grid is edited and refined by using 4 grids in θ-direction, 10 grids in r-direction and 40 grids in j-direction. The value of porosity and permeability is injected in the reservoir option. Then, the components option is clicked in order to insert the value of reservoir temperature, reservoir pressure and API gravity and select the water and oil option. The next steps are selecting the rock and fluid option after that select unconsolidated sandstone which is the condition of heavy oil reservoir and insert the value of connate water saturation and residue oil saturation. Then, the initial conditions option is clicked and

inserts the value of reservoir pressure and depth of water and oil contact. And afterward, choose the option of wells and recurrent and after that create water injector and producer at the same rate as the experiments.

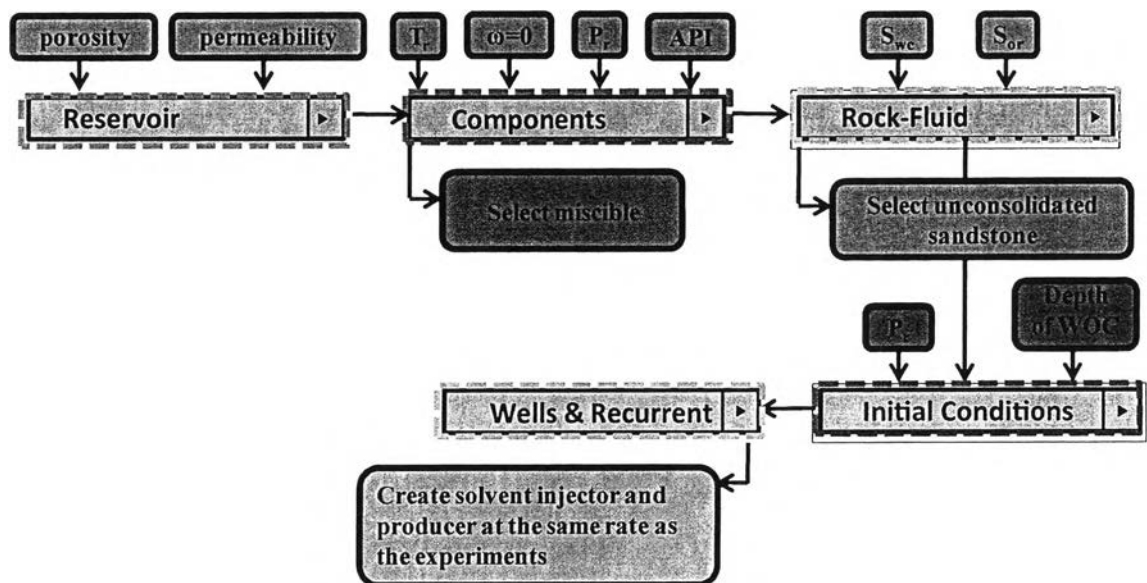### 3.5.2.2 Carbon Dioxide Flooding

Figure 3.7 Schematic diagram of simulation steps in carbon dioxide flooding.

Figure 3.7 shows the schematic diagram of carbon dioxide flooding. The most steps are the same as the simulation steps of waterflooding except the steps of components and well and recurrent. Water and oil option in the step of components is changed to be miscible option and insert the value of reservoir temperature, reservoir pressure, API gravity and mixing parameter of solvent and oil. Water injector in the step of wells and recurrent is changed to be solvent injector.

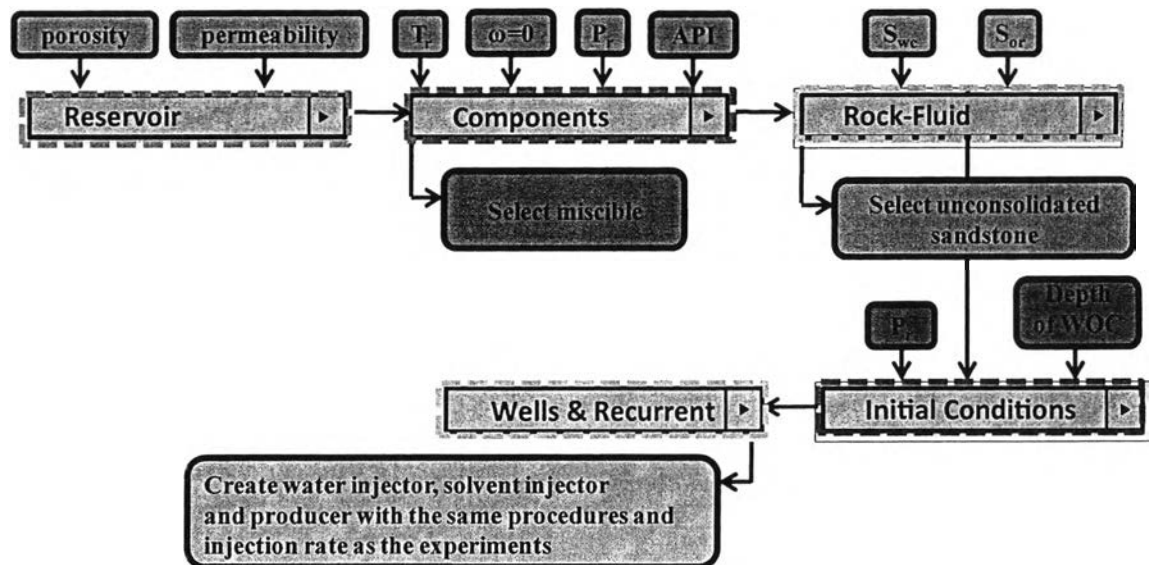### 3.5.2.3 Water-Alternating-Carbon Dioxide.

Figure 3.8 Schematic diagram of simulation steps in water-alternating-carbon dioxide.

The schematic diagram of water-alternating-carbon dioxide is presented in Figure 3.8. The major steps of water-alternating-carbon dioxide are similar to carbon dioxide flooding excluding well and recurrent step. Water injector, solvent injector and producer are created in the well and recurrent step with the same procedures and injection rate as the experiments.

3.6 Finding Error between Experimental Results and Simulation Results

A comparison between experimental result and simulation result was calculated by using the Average Absolute Relative Error (AARE). The error percentage was calculated in every test (11 tests). The percent error was calculated by recovery factor (RF) in each 0.2 pore volume. Below is presented the absolute average relative error equation.

$$AARE = \frac{1}{N}\sum_{i=1}^{N}\left(\left|\frac{Exp_i - Sim_i}{Exp_i}\right| \times 100\right)$$

(3.3)