CHAPTER IV
RESULTS AND DISCUSSION

4.1 Waterflooding Tests

The results of the simulation are a recovery factor (RF) as a function of pore volume injected. Figure 4.1 shows comparison of three waterfloodingsimulations with two different oil viscosities (test 1 and test 2) and two sand pack permeabilities (test 2 and test 3). The waterflooding of low viscosity and high permeability has the highest recovery factor. In order to compare the effect of viscosity demonstrates that when oil viscosity increased from 440 cp to 1500 cp, the recovery factor decreased approximately 12%. When sand packs permeability increased from 11.4 darcy to 38.6 darcy, there is no major change in recovery factor.

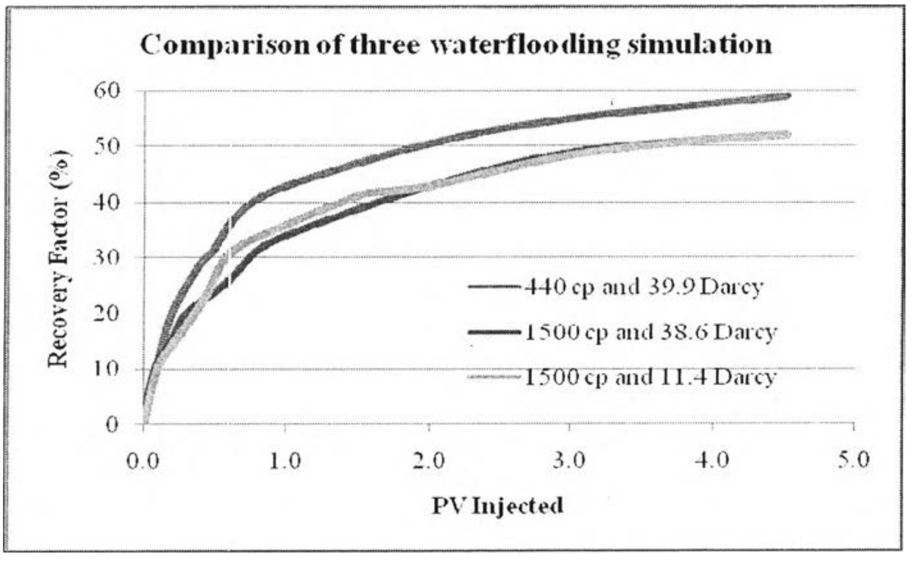

Figure 4.1 Comparison of three waterfloodingsimulations with different oil viscosities and sand pack permeabilities.

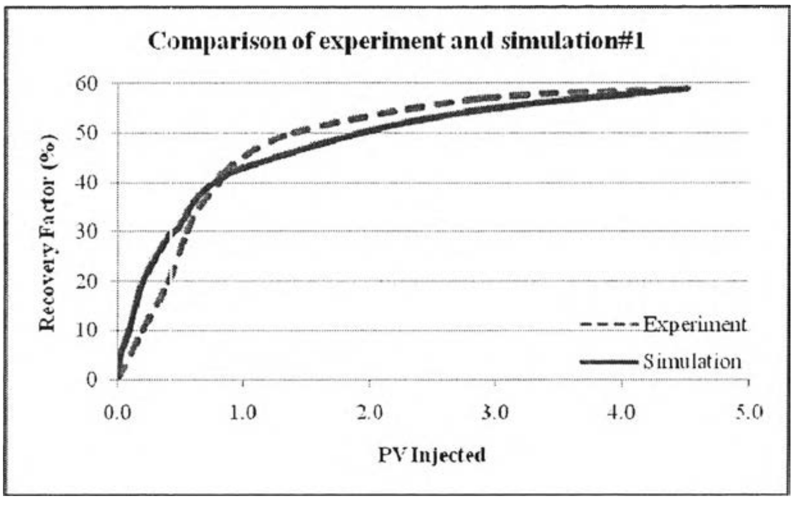

Figure 4.2 Comparison of waterflooding experiment and simulation ofhigh permeability sand pack of 39.9 darcy and low oil viscosity of 440 cp.

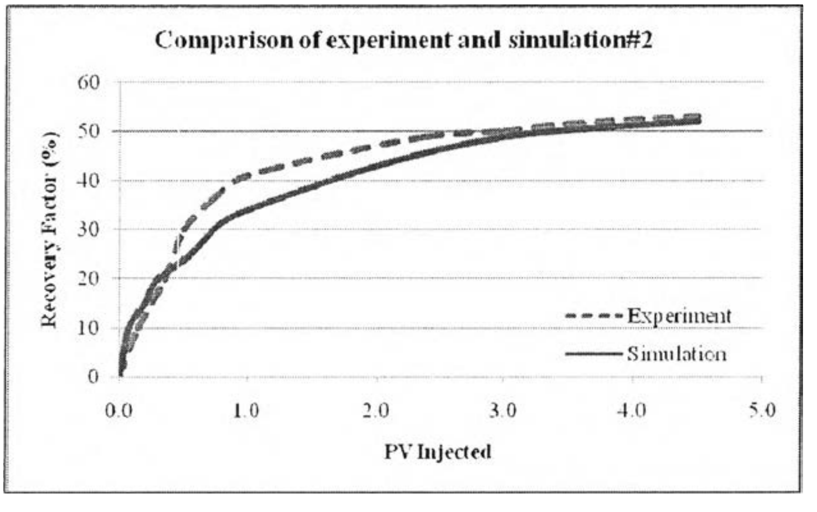

Figure 4.3 Comparison of waterflooding experiment and simulation ofhigh permeabilitysand packof 38.6 darcy and high oil viscosity of 1500 cp.

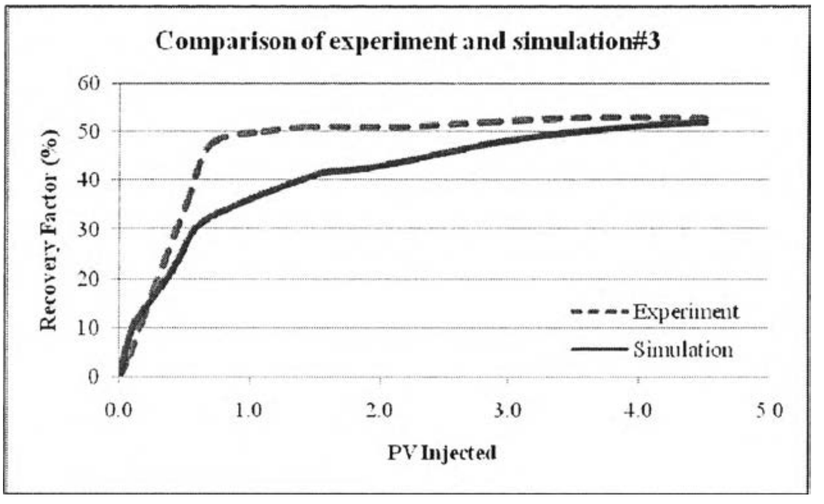

Figure 4.4 Comparison of waterflooding experiment and simulation oflow permeabilitysand pack of 11.4 darcy and high oil viscosity of 1500 cp.

Figure 4.2 through Figure 4.4show the comparison of experimental and simulation results. In case of low viscosity and high permeability (Figure 4.2), the simulation resultgives higher recovery factor than the experimental result with the deviation of 0.015%. Figure 4.3 present the case when the viscosity and permeability are both high. The performance of the simulation result, in this case, is better in terms of the recovery factor with the value of the deviation of 1.88%. When high viscosity and low permeability are taken into account, the simulation result gives poor recovery factor compared to the experimental result with the deviation of 1.88%.

4.2 Carbon Dioxide Flooding Tests

Figure 4.5 shows comparison of three carbon dioxide flooding simulations by different oil viscosities and sand pack permeabilities.Figure 4.5 shows comparison of three carbon dioxide flooding simulations with two different oil viscosities (test 4 and test 5) and two sand pack permeabilities (test 5 and test 6).Figure 4.5 can be considered that all graph demonstrated as S – shaped behavior. This behavior can be explained by carbon dioxide diffusion into the oil within the porous media which caused a lower recovery at the initial after carbon dioxide achieved the equilibrium condition between carbon dioxide and oil. The oil recovery increased continuously until reached oil breakthrough. Carbon dioxide flooding with low viscosity and high permeability has the highest recovery factor. Moreover, Figure 4.5 shows that the accelerated of carbon dioxide diffusion rate can cause more oil recovery. In order to compare the effect of viscosity demonstrates that when oil viscosity increased from 440 cp to 1500 cp, the recovery factor decreased approximately 40%. When sand packs permeability increased from 11.4 darcy to 38.6 darcy, there is no major change in recovery factor.

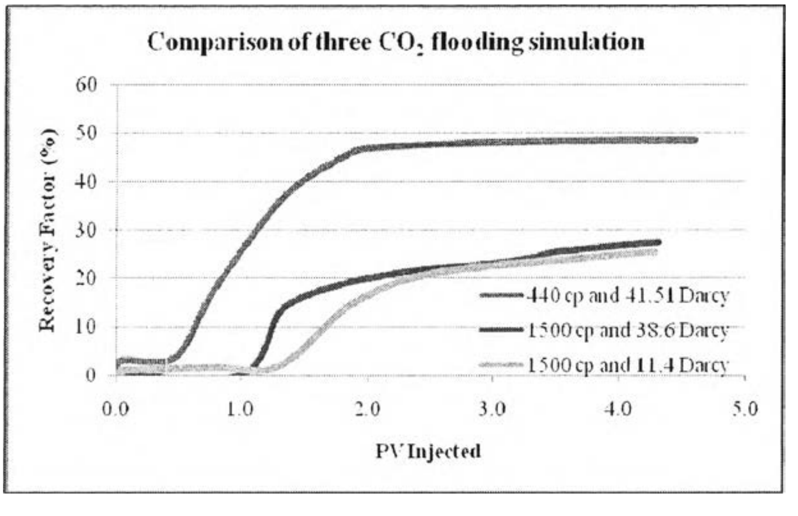

Figure 4.5 Comparison of three CO_2 flooding simulationsoftwo different oil viscosities and three sand pack permeabilities.

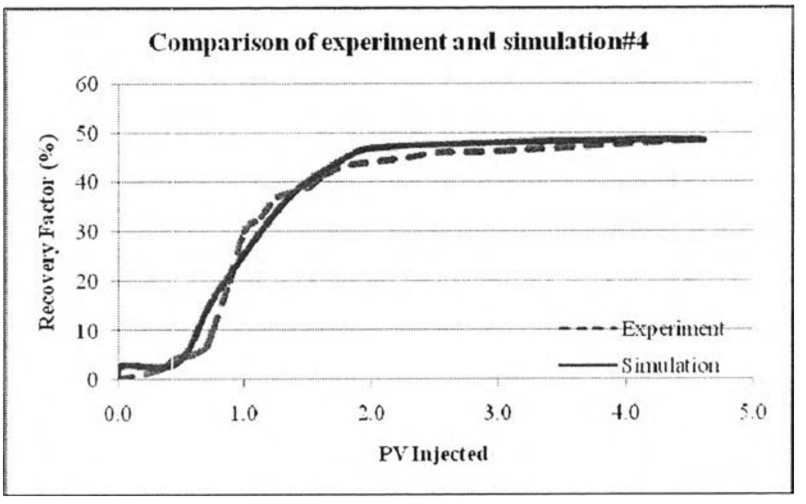

Figure 4.6 Comparison of carbon dioxide flooding experiment and simulation of sand pack with high permeability of 41.51 darcy and low oil viscosity of 440 cp.

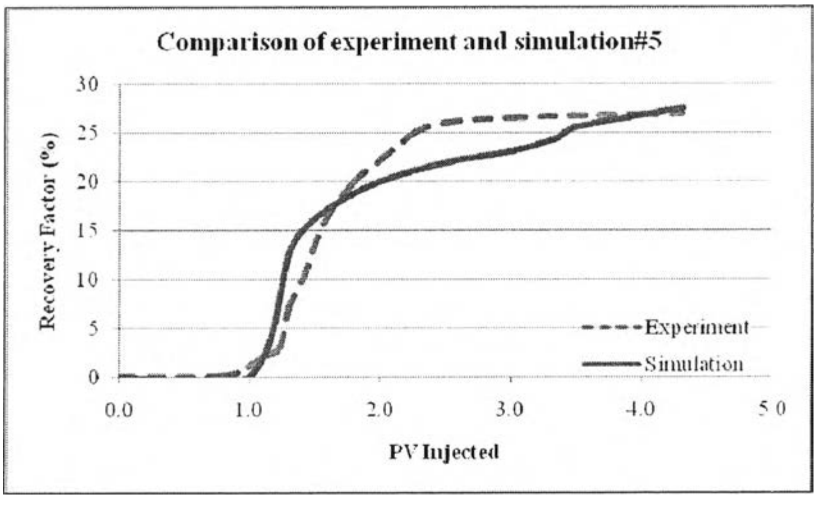

Figure 4.7 Comparison of carbon dioxide flooding experiment and simulation of sand pack with high permeability of 38.6 darcy and high oil viscosity of 1500 cp.

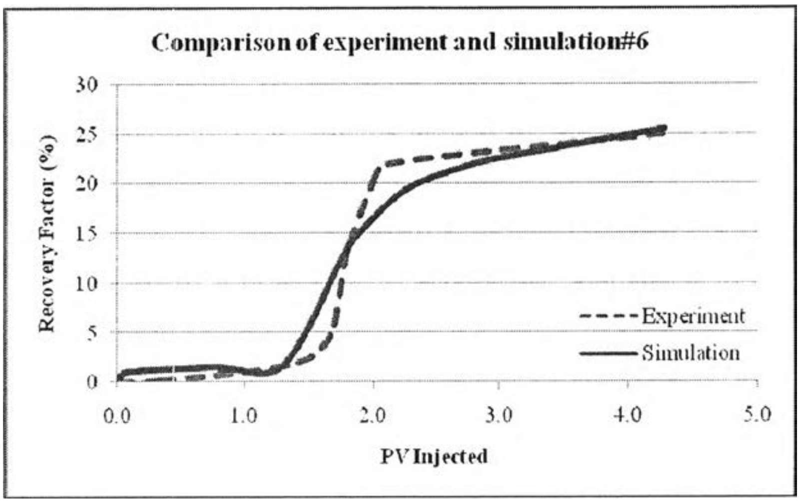

Figure 4.8 Comparison of CO_2 flooding experiment and simulation of sand pack with low permeability of 11.4 darcy and high oil viscosity of 1500 cp.

Figure 4.6 through Figure 4.8 shows the comparison of experimental and simulation results. Figure 4.6 presents the case of low oil viscosity and high permeability, indicating that there is insignificant difference between the simulation and experimental result. For both high oil viscosity and permeability as shown in Figure 4.7, the simulation result exhibits the recovery factor better than that of the experimental result with the deviation of 1.11%. As observed from Figure 4.8, in the case of high oil viscosity and low permeability, there is trivial change between the simulation result and the experimental result.

4.3 Water-Alternating-Carbon Dioxide Flooding Tests (CO_2-WAG)

Figure 4.9 shows five CO_2-WAG tests with different oil viscosity (test 7 and test 8), sand pack permeability (test 8 and test 9) and various CO_2/water slug ratios of 1:1, 1:2 and 2:1 (test 8, test 10 and test 10) were performed to consider the performance of CO_2-WAG method for enhancing heavy oil recovery. In order to compare the effect of viscosity demonstrated that when oil viscosity increased from 440 cp to 1500 cp, the recovery factor decreased approximately 20%. When the sand pack permeability increased from 11.4 darcy to 38.6 darcy, there was no major change in recovery factor. The CO_2/water slug ratio of 1:1 demonstrates superior value in term of recovery factor comparing with The CO_2/water slug ratio of 1:2 and 2:1 with the deviation of 20.38% and 17.19%, respectively.

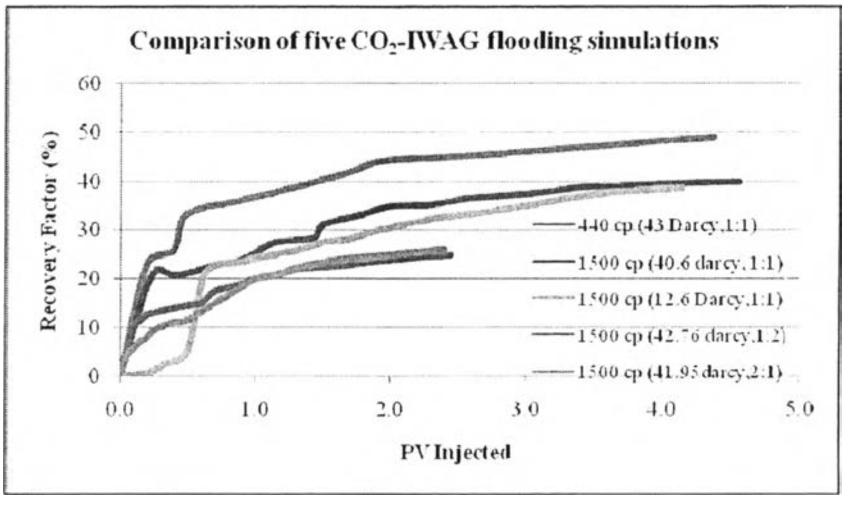

Figure 4.9 Comparison of five CO_2-WAG flooding simulation of different oil viscosities, sand pack permeabilities and CO_2/water slug ratio.

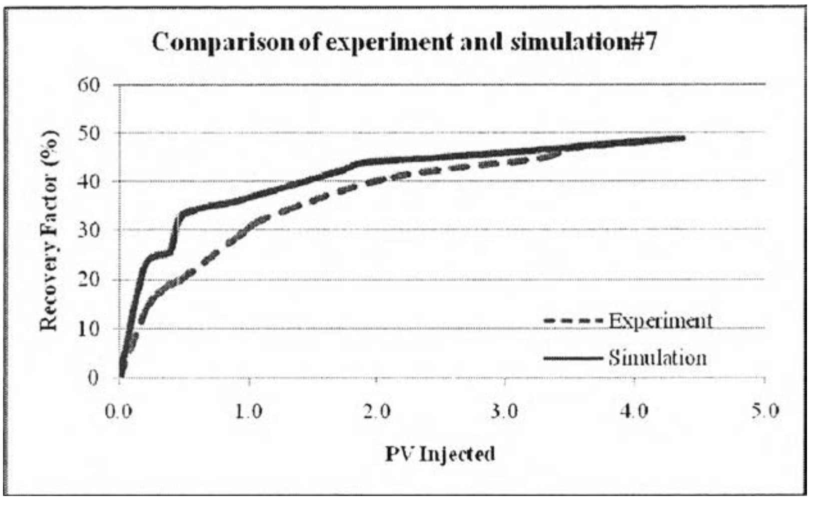

Figure 4.10 Comparison of CO_2-WAG flooding experiment and simulation of sand pack with high permeability of 43darcy,low oil viscosity of 440 cp and CO_2/water slug ratio of 1:1.

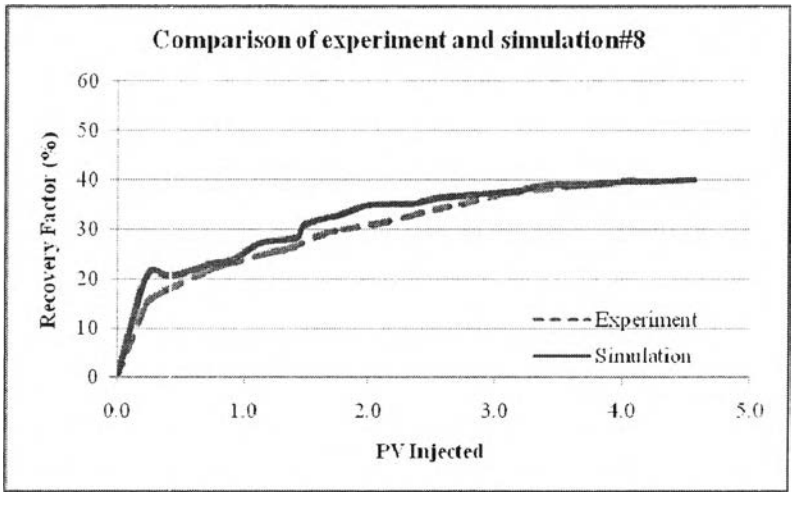

Figure 4.11 Comparison of CO_2-WAG flooding experiment and simulation of sand pack with high permeability of 40.6 darcy, high oil viscosity 1500 cp and CO_2/water slug ratio of 1:1.

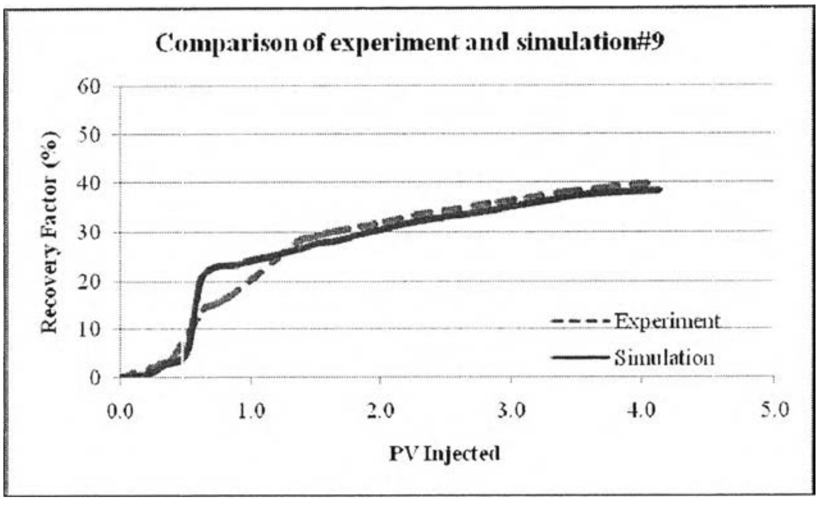

Figure 4.12 Comparison of CO_2-WAG flooding experiment and simulation of sand pack with low permeability of 12.6 darcy, low oil viscosity of 440 cp and CO_2/water slug ratio of 1:1.

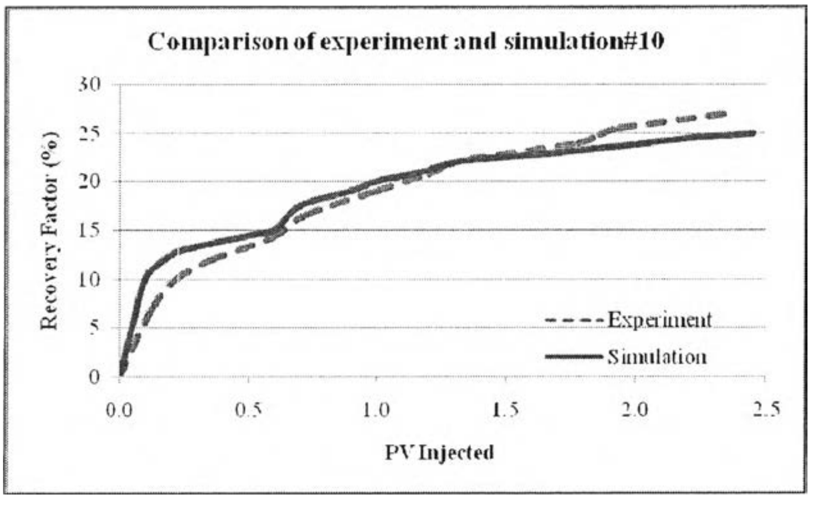

Figure 4.13 Comparison of CO_2-WAG flooding experiment and simulation of sand pack with high permeable of 41.95 darcy, high oil viscosity of 1500 cp and CO_2/water slug ratio of 1:2.

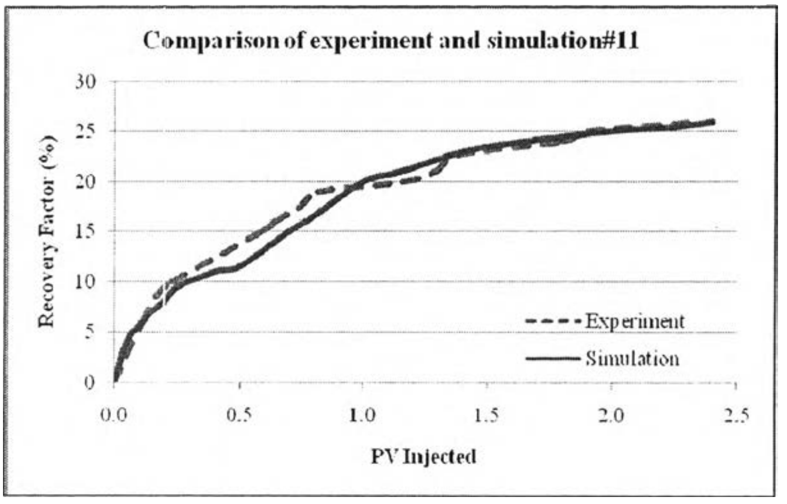

Figure 4.14 Comparison of CO_2-WAG flooding experiment and simulation of sand pack with high permeability of 42.76 darcy, high oil viscosity of 1500 cp and CO_2/water slug ratio of 2:1.

Figure 4.10 through Figure 4.14show the comparison of experimental and simulation results. In the case of low oil viscosity, high permeability and CO_2/water slug ratio of 1:1 as illustrated in Figure 4.10, the outcome of the simulation and experiment has no difference in terms of the recovery factor. For the case of both high oil viscosity and permeability with the CO_2/water slug ratio of 1:1 (Figure 4.11), the recovery factor of the simulation result give slightly better performance than the experimental result with the deviation of 0.25%. In Figure 4.12, the recovery factor of the simulation result demonstrates higher value than the experimental result with the deviation of 3.75% for the case of high oil viscosity, low permeability, and the CO_2/water slug ratio of 1:1. For high oil viscosity, high permeability, and the CO_2/water slug ratio of 1:2 (Figure 4.13), the experimental result demonstrates superior value in comparison with the simulation result with the deviation of 7.40%. In the case of high oil viscosity, high permeability, and the CO_2/water slug ratio of 2:1 as depicted in Figure 4.14, there is no considerable change in the recovery factor of the simulation result and the experimental result.

4.4 Error Comparison

A comparison between experimental result and simulation result was calculated foran average absolute relative error (AARE) and presented in Figure 4.15.The maximum AARE is less than 8 % in every test.In case of high oil viscosity and high permeability in carbon dioxide flooding (test 6) has the lowest AARE of 4.29 % and for the case of low oil viscosity, high permeability and the CO_2/water slug ratio of 1:1 (test 7) has the highest AARE of7.19 %.

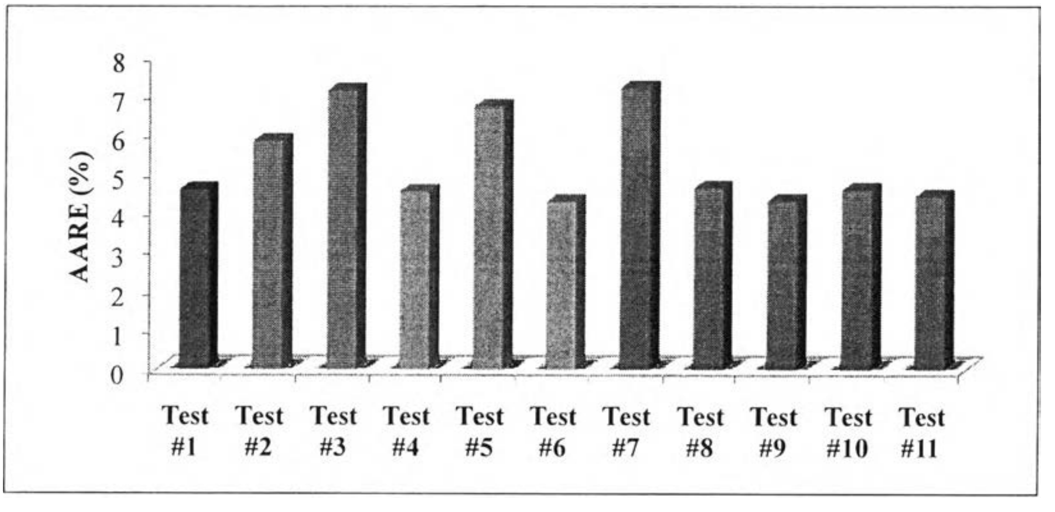

Figure 4.15 Averageabsolute relative error (AARE) calculated for each test and different recovery factor (RF) at every 0.2 PV.

The different enhanced oil recovery (EOR) methods based on the simulation results show that the waterflooding gained the highest amount of recovery followed by CO_2-WAG and CO_2 flooding, respectively. The trends of oil from the simulation results were similar to experimental data. The waterfloodingwas more effective than the other flooding methods because water viscosity is higher than carbon dioxide. According to the mobility ratio as expressed in equation 4.1 showing the relationship of viscosity and mobility ratio, the mobility ratio of oil to water will be less than the mobility ratio of oil to CO_2; therefore, the waterflooding created more favourable displacement than CO_2 flooding. Moreover, fingering effect will be generated at high mobility ratio more than low mobility ratio.

$$M = \frac{k_{rw}\mu_o}{k_{ro}\mu_w} \quad (4.1)$$

Where M is mobility ratio

k_{rw} is relative permeability of water

k_{ro} is relative permeability of oil

μ_w is viscosity of water

μ_o is viscosity of oil

The main notable of carbon dioxide flooding in heavy oil is the reduction in oil viscosity. The viscosity of oil saturated with carbon dioxide is a function of temperature and pressure. In general, the lowest temperature of heavy oil is approximately 25 °C and the lowest pressure is approximately 700 kPa(Metwally, 1998; Miller *et al.*, 2003; Naylor *et al.*, 2000). However, the pressure in this simulation was extremely lower than regular pressure in heavy oil reservoir. At this pressure carbon dioxide was not able to mobilize the oil as positively as the water.

The main objective of water-alternating-carbon dioxide in heavy oil is the reduction in oil viscosity by using carbon dioxide slug. Moreover, this process has water's displacement mechanism to create more oil recovery. As the result, it should not consider that carbon dioxide flooding and water-alternating gas process are necessarily less effective than waterflooding. Hence, different operating condition should be tested to obtain appropriate condition for enhancing heavy oil recovery.

The simulation results were compared to the experimental results with the average value of AARE 5.30%. The percent error of this simulation results might come from the various factors which will be discussed below.

- Shapes of the simulation models are not similar to the sand pack in the previous experiments due to the limitation of software.
- The permeability and porosity in this simulation model are assumed as homogeneous in all direction which might not be the same condition as the previous experiments.
- If more experimental data could be collected, the percent error might be reduced.