Experiment and simulation on heavy oil production with steam flooding in heterogeneous reservoir

K Maneeintr¹, K Sasaki² and T Boonpramote¹

1 Carbon Capture, Storage and Utilization Research Group, Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
2 Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka, Japan

Corresponding author: Krengkrai.M@chula.ac.th

Abstract. Heavy oil has long been known as one of the main energy sources due to the huge amount of reserves. Heavy oil production depends on reservoir characteristics like permeability, reservoir pressure as well as oil viscosity. The difficulty to produce this oil is its high viscosity. The practical technology to produce this heavy oil is to use steam as steam-flooding method to reduce oil viscosity. However, the huge energy consumption in steam-flooding operation can impact the operating cost as well as a project life. Therefore, the objectives of this study are to measure the viscosity and correlate the results with temperature and to simulate the oil production by using STARS, a CMG program. Moreover, the effects of parameters like well distance, injection rate and permeability on the oil production are also investigated. The simulation results show that oil viscosity and permeability play significant roles in heavy oil production. Also, the higher oil recovery can be obtained by increasing the steam injection rate and shorten the well spacing. These conditions can be applied to use in the real field for heavy oil production. The major benefit of this practice is to reduce the steam consumption and fuel costs and increase more oil production thus extending the economic project life.

1. Introduction
Heavy oil has long been known as one of the main energy sources because of the huge amount of reserves and higher demand of oil consumption [1]. Heavy oil production depends on reservoir characteristics like permeability, reservoir pressure as well as oil viscosity. However, with the high viscosity of heavy oil, the practical technology to produce this heavy oil is steam-flooding method, one of the main techniques for enhanced oil recovery [2-3]. In fact, the steam-flooding performance can be linked to several design parameters such as oil recovery, well spacing, steam injection rate and amount of steam used. Steam consumption per oil production or cumulative steam-oil ratio (Cum SOR) can be used as a criteria to consider the steam-flooding method. Also, to determine the favorable operating conditions, many recent researches have been studied [4-5]. Therefore, the objectives of this study are to measure the viscosity and correlate the results with temperature and to simulate the oil production by using STARS, a CMG program with the five-spot pattern. Furthermore, the effects of parameters such as well distance, injection rate and permeability on the oil production are also investigated. These operating conditions can be applied to use in the real field for heavy oil production. The major benefit
of this practice is to reduce the amount of steam consumption and fuel costs and to increase more oil production. Therefore, the project life of oil production can be extended and economically viable.

2. Viscosity measurement

2.1 Equipment and procedure
Oil viscosity and its emulsions are measured with the effect of temperature at 6.58 and 3.20 oil/water ratio. The measurement temperature ranges from 15 to 180°C. The viscosity measurement is carried out by Brookfield cone/plate programmable viscometer Model DV-III, using a cone spindle with various numbers. The viscosity measurement is performed with the accuracy of ± 1.0°C. The accuracy of viscosity measurement is ± 1.0% accuracy of full scale range for a specific spindle running at a specific speed. Allow enough time for the sample to reach equilibrium. Each sample can be measured 3 times to get the average result. Calibration can be done with standard solution supplied by Brookfield.

2.2 Experimental results
Heavy oil and its emulsions are measured at temperatures from 15-180°C as presented in Figure 1. From the results, it is obvious that the viscosities decrease as the temperature increases because of thermal energy. The viscosities of the mixture of oil and steam or emulsions with 6.58 and 3.20 oil/water ratio (O/W) are higher than that of original oil for the whole concentration range.

These phenomena can be explained by the fact that crude oil, especially the heavy oil, contains the large quantities of asphaltenes (high molecular weight polar components) that act as natural emulsifiers. Other crude oil components are also surface active: resins, fatty acids such as naphthenic acids, wax crystals, etc. These substances contain hydrogen bonds in the heavy oil molecule. When steam is present in heavy oil, hydrogen bonds are formed following interactions between components and water. Hydrogen bonds can create irregular properties deviated from mixing rules such as maximum or minimum peak for viscosity of mixture [6-7].

![Figure 1. Effect of temperature on viscosities of oil and its emulsions](image)

3. Correlation for viscosity measurement
The correlation of viscosity as a function of temperature to relate the experimental data is developed based on the ones from the literature [7-9] as presented in equation 1. Therefore, as shown in Figure 1, the calculated results from correlation are calculated and compared with the experimental results. This correlation is in the form as shown below:

\[ \mu = A T^B \]  

(1)

Where \( \mu = \) viscosity (cP),
T = temperature (°C)
A and B = coefficients

In addition, the average absolute deviations (AADs) between experimental and calculated values is 12.92%. Therefore, this correlation can be acceptable to predict the viscosity of heavy oil.

4. Simulation

4.1 Reservoir model
The simulation study is performed by using STARS program from Computer Modeling Group (CMG). The reservoir model is constructed from the actual field data such as permeability ranging from 1,000 to 25,000 mD. The inverted 5-spot pattern [10] which has an injection well at the center and 4 production wells at the corners with 80% steam quality is used in this study as illustrated in Figure 2. The three different well distance from 150 to 250 m are evaluated by considering the production efficiency and recovery factor (RF) with various injection rates ranging from 20-100 m³/d.

![Figure 2. Reservoir model simulation](image)

4.2 Simulation results

4.2.1 Effect of permeability on oil production. Practically, the permeability of the well can be varied randomly from low to high. However, to investigate the effect of permeability, the average permeabilities are estimated at 1000, 5000 and 25000 mD which are the average of the field data for each area. The effect of permeability on the percent recovery factor (%RF) and cumulative steam oil ratio (SOR) is shown in Figure 3.

![Figure 3. Effect of permeability on cumulated oil production and steam oil ratio](image)
It is relatively clear that at high permeability, the oil production is higher compared to that at low permeability because the fluids can flow easily and steam injection rate can be reduced. This condition is conducive to heavy oil production. From SOR point of view, it can be reduced significantly as permeability increased especially from 5000 mD to 25000 mD. This means less amount of steam is needed to produce heavy oil. Compared to 5000 mD, the cumulative oil productions at 1000 and 25000 mD are 8.19 % lower and 26.59 % higher, respectively and consumed SOR are 6.47 % higher at low permeability and 19.64 % lower at high permeability.

4.2.2 Effect of well distance on oil production. The results of the effect of well distance on oil production is presented in Figure 4. From the results of three different injector-producer distances, 150, 200 and 250 m, it presents that the shorter distance provides higher oil recovery than of the longer one. However, the cumulative SOR is decreasing with an increasing distance.

![Figure 4. Effect of well distance on cumulated oil production and steam injection](image)

It is evident that, compared to base case at 200 m, the cumulative oil production improves for 18 % when the area is larger and reduces 27 % when using smaller area. However, the cumulative steam oil ratio will increase approximately for 37 % for small area and decreases 15 % for 250 m well distance. Moreover, the well distance at 150 m consume high SOR. As a result, the cost of steam will be increased.

4.2.3 Effect of steam injection rate on oil production. Figure 5 illustrates the effects of oil recovery and the cumulative SOR for various steam injection rates ranging from 20-100 m$^3$/d. It is noted that the higher steam injection rate can increase both the total oil recovery and SOR. The injection rate at 100 m$^3$/d yields the highest RF at 43.58 %. However, the cumulative SOR is also the highest at 4.48 which means the cost of steam would be higher as well.

![Figure 5. Effect of steam injection rate on cumulated oil production and steam injection](image)
From the results, the cost of steam will be increased. Consequently, for practical work, to reduce the steam-oil ratio, the injection rate can be lowered with high permeability reservoirs. However, the economic point of view is required to decide the optimal condition for this area by consideration from the previous study with steam injection [11-12]. Subsequently, the conditions can be applied in the real field for heavy oil production.

5. Conclusions
Oil viscosity and its emulsions are measured and correlated over the entire temperatures ranging from 15 to 180°C. When steam is used, emulsion is formed and effect of hydrogen bonds on the viscosity has been explained. Moreover, the experimental data are correlated as a function of temperature based on the form in literature. The average absolute deviation is calculated at 12.92 %. Therefore, the correlation is suitable to represent the experimental data of viscosity of heavy oils and their emulsions.

For the simulation, the fluid properties and reservoir conditions are required to perform the simulation. Also, the parameters such as permeability, well distance and steam injection rates are essentially needed to be investigated for their effects on heavy oil production. The five-spot pattern is selected for simulation because it is effective and economical method for heavy oil production. From the simulation results, all parameters play a key role in heavy oil production. The recovery factor increases as permeability and injection increase and well distance decreases. Furthermore, steam-oil ratio would be reduced if injection rate is lowered with high permeability reservoirs. These conditions can be applied in the real field for heavy oil production. The main contribution of this practice is to reduce the steam consumption and fuel costs and to increase more oil production as well as to prolong the project life.

6. Acknowledgement
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