# CHAPTER V
# RESULTS AND DISCUSSION FOR CONSOLIDATED ROCK

## 5.1 Rock Characteristic

Sandstone was chosen as a consolidated porous media in this part of the study. The dimensions of the sandstone are presented in Figure 5.1, i.e. a length of 4.8 cm and a diameter of 2.5 cm. This rock shows a fine-grained texture of a beige/yellow color. The rock core sample has a longitudinal fracture. It also shows a small central circular dent at the bottom, a 1.2 cm long shallow dent on top, and a top rounded edge.

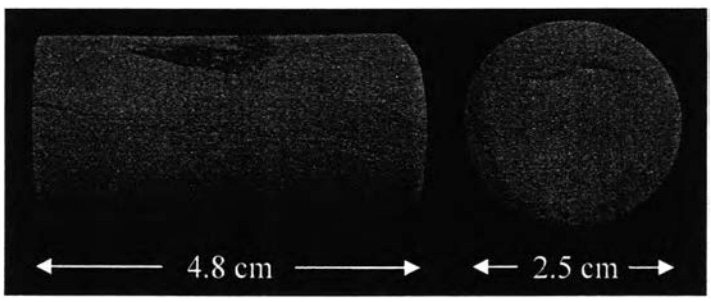



**Figure 5.1** Photograph of sandstone with dimensions

The rock was saturated with deionized water in a vacuum unit. The pore volume and porosity were measured by weighting dry rock and the saturated mass rock. The permeability of this rock was obtained by using a high-pressure pump with core holder. Pump model QX-6000-SS, Vindum Engineering, San Ramon CA and core holder model FCH-1, Temco Inc. were used in this experiment. Table 5.1 shows the properties of the rock at room temperature (~25 °C).

**Table 5.1** Sandstone properties

| | |
|---|---|
| Pore Volume | 6.19 ml |
| Porosity | 26.27 % |
| Permeability | 92.7 mD |

## 5.2 Waterflooding Process

Two waterflooding experiments were conducted. In the first experiment, Fluorolube FS-5 was used as the oil phase. The $^{19}F$ signal was detected, the imaging from MRI show the signal intensity of fluorolube oil (bright areas) and water (dark areas).

In the second experiment, dodecane was selected to represent the oil phase. To distinguish the $^{1}H$ signal of the oil from the injected water, heavy water ($D_2O$) was chosen as the displacing phase. The signal intensity of dodecane is shown in bright areas and heavy water is shown in dark areas. A material balance and MRI calculation were applied in these experiments to monitor the efficiency of the flooding process.

### 5.2.1 Fluorolube Oil Experiments

An initial oil saturation of 81.89 % was observed before the waterflooding process. The injection of 19.25 ml of water (3.11 PV) at a constant flow rate of 0.06 ml/min was used. Figure 5.2 shows the oil saturation profile from an integral total MRI signal. The images acquired through the waterflooding process, which correspond to Figure 5.2, are shown in Table 5.2. The experiments reveal the benefit of this technique in order to visualize the inhomogeneous structure of the rock core sample.

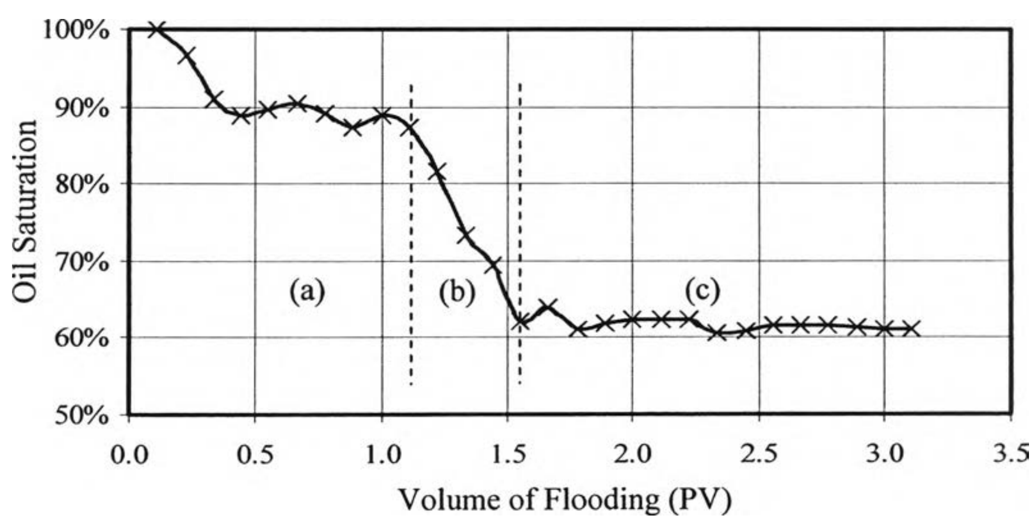
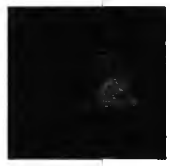
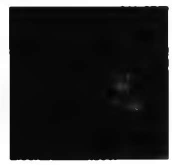



**Figure 5.2** Residual oil saturation ($S_{or}$) profile from MRI for fluorolube oil experiments in sandstone

**Table 5.2** Images of waterflooding test for fluorolube oil experiments in sandstone

| Corresponding to | Images at each PV | | |
|---|---|---|---|
| Figure 5.2 (a) | <br>0.111 | <br>0.555 | <br>1.111 |
| Figure 5.2 (b) | <br>1.222 | <br>1.333 | <br>1.444 |
| Figure 5.2 (c) | <br>1.555 | <br>2.332 | <br>3.110 |

The first image of 0.111 PV in Table 5.2 shows the initial stage of the rock core sample. From this image, the oil saturated some major parts of the rock (in the bright areas). After 0.555 PV of waterflooding, 10 % of the oil in the front part of the rock was displaced. Then, the rate of flooding was constant for approximately 0.5 PV of water according to Figure 5.2 (from 0.5 PV to 1.0 PV). The images show less significant change in term of fluid saturation from 0.555 to 1.111 PV. In this first stage of the displacement process, some oil was flooded from the first half of the rock. From 1.222 to 1.444 PV, a dramatic change was detected from the images in term of the residual oil saturation profile. The second half of the rock which contained the majority of oil, it was efficiently recovered. The significant decrease of 30 % in the residual oil saturation profile corresponds to the oil displaced by water from the images. Finally, the waterflooding process reached the plateau and leveled off at 61.1 % as shown in Figure 5.2. The images illustrated that this waterflooding displacement is very inefficient after 1.555 to 3.110 PV.

The residual oil saturation, $S_{or}$, calculated from a material balance was 42.8 %. A high deviation between MRI quantification and the material balance of 18.3 % was observed. This first experiment of visualization and quantification in the rock core sample was the preliminary step of the centric scan SPRITE MRI technique. Many factors limited the performance of this measurement. Improvements to the SPRITE MRI technique need to be developed for consolidated rock core samples.

### 5.2.2 Dodecane Experiments

An initial oil saturation of 99.13 % was measured before the waterflooding process for this rock core sample. The injection of 3.44 ml of water (0.56 PV) at a constant flow rate of 0.06 ml/min was used in this experiment. Since dodecane is a light oil (Specific gravity of 0.748), the whole process is relatively fast compared with the previous experiment. Figure 5.3 shows the oil saturation profile from the integral total MRI signal and MRI acquired images during the waterflooding process.

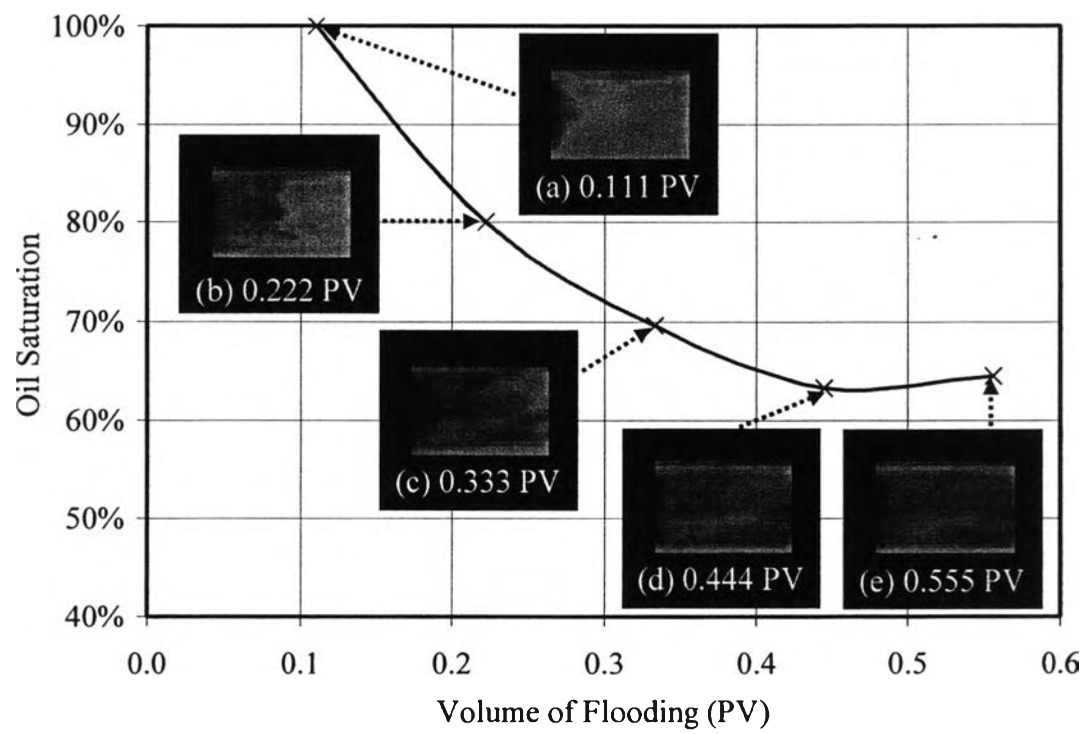



**Figure 5.3** Residual oil saturation ($S_{or}$) profile and images for dodecane experiments in sandstone

In this displacement experiment, the same rock core sample from the previous displacement test (fluorolube oil experiments) was used as the porous medium. The oil phase was changed to dodecane and the aqueous phase used in this case was heavy water ($D_2O$). The signal from $^1H$ was detected from the oil phase. Figure 5.3 (a) shows the rock core sample after the injection of 0.111 PV. The image shows a high intensity of oil contained in the rock (bright areas). After the second acquired image at 0.222 PV, the oil in the first-half length of the rock was displaced. The process is extremely fast since the dodecane is a comparatively light oil leading to a good mobility ratio for the displacement process. 35 % of oil was recovered after the injection of 0.555 PV of water, whereas the displacement process was finished.

The oil saturation profile in Figure 5.3, shows the monitoring of the waterflooding process using MRI, the residual oil saturation ($S_{or}$) of 64.3 % was calculated. While residual oil saturation, based on a material balance was 44.6 %. A deviation of 19.7 % was detected which reflects the quantitative problem of this technique in a consolidated rock core sample.

Unfortunately, the high deviation between the MRI quantification and the material balance is the limitation of this technique. Nevertheless, the images of fluid distributions and residual oil saturation ($S_{or}$) profiles from the MRI allow a better understanding of the structures and dynamic microscopic processes in a porous media.