Flow Visualization Studies of Two Phase Flow Through Layered Porous Media

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Abstract: Water flooding is the most widely used process for for extracting oil from reservoirs. Since oil reservoirs are heterogeneous in nature, it is of utmost importance to understand the physics associated with the flow of fluids in these reservoirs to better predict production performance. This paper focuses on the effect of reservoir heterogeneities on the waterflood (immiscible displacement) process. Experiments are performed using two–dimensional flow model packed with sand particles of different size to form layers of different permeability. This experimental study demonstrates the significant effect of heterogeneity on flow pattern. It is observed that during waterflooding, high permeability regions are bypassed due to capillary pressure difference. This serves to understand the flow physics in stratified reservoir and can assist in understanding waterflood performance of actual reservoirs.

Key–Words: immiscible displacement, permeability, heterogeneity, capillary pressure, two–dimensional model

1 Introduction

In most oil reservoirs, permeability and porosity varies from location to location [1]. These heterogeneities are caused by faulting and sedimentological complexities. Due to these heterogeneities the fluid flow path deviates from that of homogeneous system and results in a variation of fluid distribution within the reservoir rock and the resultant production performance. These heterogeneities occur at all scales from kilometers down to microns. The analysis of heterogeneities are important not only to determine the distribution of oil within the swept zones and the distribution of by-passed oil, but also the initial distribution of oil in reservoir.

Heterogeneities, if not properly accounted for at planning stages of oil recovery operations, only become evident later in the life of the oil recovery project, when water break through occurs earlier than predicted. Thus, enhanced oil recovery (EOR) processes, if undertaken without detailed reservoir evaluation, often end up in failure due to poor understanding of the effect of these heterogeneities on fluid displacements. Understanding the movement of fluid within the heterogeneous porous media is therefore fundamental to petroleum production and its efficient management.

A thorough understanding of the physics of flow in heterogeneous system can only be attained by use of lab visual models having well defined heterogeneities. It is essential that the process occurring in heterogeneous model be correctly understood, in order to improve prediction method for oil recovery and water control techniques at the reservoir scale. The precise effects of such heterogeneities depends upon the actual oil recovery process employed and on the associated balance of forces [2].

Layered systems with permeability heterogeneity at the reservoir scale have been extensively studied [3, 4]. However, a very few flow visualization studies have reported the effect of heterogeneity in the permeability within core [5]. Dawe et al.[6] carried out extensive visualization experiments to study the effect of well defined heterogeneity of porous media on immiscible flooding. They modeled layers and lenses, with some lenses of wettability contrast. Their results show that the balance between capillary and viscous forces is rate dependent. In displacement through layered(lens) system, capillary forces dominate the local flow around the permeability discontinuities.

Cinar et al. [7] presented flow visualization experiments and numerical simulation to demonstrate the combined effect of viscous forces, capillary forces and gravity segregation on cross flow that occurs in two phase displacement in layered porous media. By a series of experiments they quantified the transition between the capillary, viscous and gravity forces. Low rate drainage/imbibitions flood experiments are performed by Huang et al.[8] in a $20 \times 10 \times 1$ cm water–wet slab of cross laminated heterogeneous sandstone. The low rate floods showed that between 30–50$\%$ of

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original oil was trapped in isolated high permeability lamina. Thus they showed the importance of recognizing the role of core scale heterogeneity in laboratory measurement of waterflood.

Roti and Dawe [9] performed experiments and numerical simulations to study the effects of layer thickness, permeability contrast, angle of layer to flow direction, mobility ratio and flood rate. They found that each of these parameters influence the displacement profiles, and disperse the flood front and such real effects must be considered when using reservoir heterogeneities in average reservoir parameters in simulation studies.

Many studies have been reported on stratified reservoir, however, a very few experimental visualization studies have been performed to study the change in flow pattern due to heterogeneity. Present experimental investigation is aimed at to study the change in flow pattern in case of stratified reservoir so that the underlying flow physics for such flow behavior can be better understood.

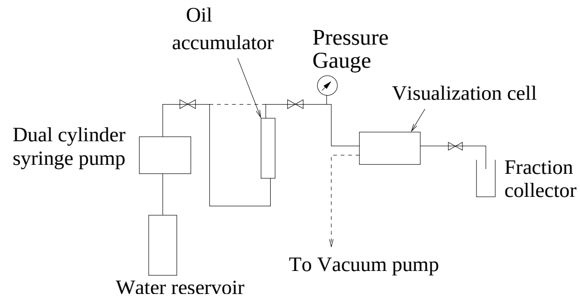

Figure 1: Schematic of experimental apparatus

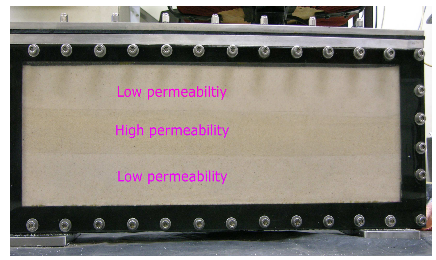

Figure 2: Layers of different permeability in visualization cell

2 Experiments

The schematic of experimental apparatus is shown in Fig. 1. The apparatus consists of a dual cylinder precision syringe pump for injection, oil accumulator, and a two–dimensional flow visualization cell. The pump injects the water either directly to the cell or to displace the oil from accumulator. The dotted line in Fig. 1 indicates the bypass of oil accumulator during waterflooding. The visualizaiton cell consists of stainless still with one side made up of Plexiglas for visualization. The working dimensions of the model are $60 \times 2 \times 20$ cm with a series of ports on three sides for mounting wells. The cell is filled with three sand layers of equal thickness with two different sand particle sizes viz., ASTM 40(425 microns) and ASTM 30(600 microns). The middle layer is modeled as a high permeability layer made up of ASTM 30 sand whereas top and bottom layers are low permeability layers contains ASTM 40 sand as shown in Fig. 2. The ratio of absolute permeabilities of high and low permeable layer is 2.

Stainless steel tubes of 8 mm diameter with perforations of 3 mm diameter along its length are used as wells. These tubes have a perforation density of 28 holes per sq. inch. The tubes are covered with a metal screen of 150 mesh size to prevent the sand from entering inside the well. Wells are placed at appropriate location depending upon the experiment carried out.

The sand pack is then tested for leakage with soap bubble test using high pressure nitrogen upto 2 bar pressure. When constant pressure is maintained for half an hour, it is assumed that the pack is leak–proof. The pack is then evacuated using a vacuum pump(740 mm Hg of vacuum is achieved) followed by water saturation process to determine the pore volume(PV) of the sand pack. In water saturation process, the water is allowed to flow by gravity into the sand pack. Pore volume is then determined by the amount of water absorbed by the pack. Water and paraffin oil are used as the displacing and displaced fluids, respectively. The absolute viscosities of water and oil are 0.97 and 130 cP, respectively measured at temperature of $25°C$. The water and oil are colored with red and yellow dyes for better visualization.

After water saturation, paraffin oil is injected to displace the water to irreducible water saturation (S_{wi}). The condition of irreducible water saturation is ensured when no more water is observed in the effluent. After the cell is prepared for the displacement experiments, waterflooding is carried out with a constant injection rate of 50 ml/hr. All waterflooding experiments are performed at constant room temperature of $25 \pm 1°C$ and atmospheric pressure. Photographs during oilflood and waterflooding have been taken at regualar intervals with digital camera.

The total four sets of experiments, Set 1 to 4, have been performed with different injection well perforation configurations. These are shown in Fig. 3 in which Figs. 3a through 3d correspond to Set 1 to Set 4, respectively. In sets 1 to 3, the middle layer of sandpack is of high permeability whereas top and bottom layers are of low permeability. In Set 4, the order of layers is reversed in which middle layer is low permeable whereas top and bottom layers are high permeable. In all experiments, the vertical injection–vertical production well configuration is used. Production well is fully perforated along its length whereas an injection well is perforated at different locations. The porosity and irreducible water saturation values for all the experiments are provided in Table 1.

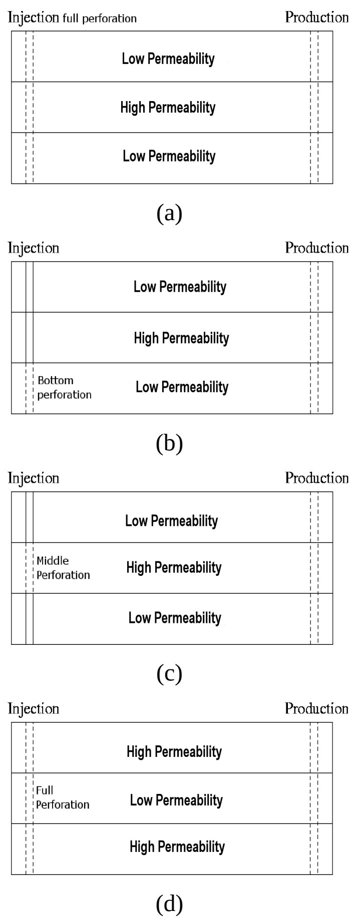

Figure 3: Schematic of visualization cell with layered porous media and different well configurations.

Table 1: Experimetal data

Experiment	Layer permeability configuration	Porosity	S_{wi}
Set 1	Low-High-Low	46.0%	28.0%
Set 2	Low-High-Low	50.4%	11.0%
Set 3	Low-High-Low	50.8%	11.7%
Set 4	High-Low-High	48.5%	10.5%

3 Results and Discussion

The results of flow visualization experiment for different configurations are presented in this section. At the start of every case, the pack is fully saturated with water and then it is saturated with oil, which is followed by waterflooding.

3.1 Set 1

As shown in Fig. 3a, visualization experiments are performed with fully perforated vertical and horizontal well pattern. The oil saturation and waterflood profiles are shown in Fig. 4. It is observed that during oil saturation (Fig. 4a through 4c), oil takes the path of high permeability (middle layer) and reaches the production well much earlier than that of in the top and bottom low permeable layers. As the injection continues the oil flows through the middle layer, causing a difficulty in establishing uniform oil saturation in the sandpack. For achieving uniform oil saturation in sandpack, the flow rate is increased from 50 to 150 ml/hr in step of 50 ml/hr.

After establishment of uniform oil saturation, water flooding is performed and a very interesting phenomena is observed. As opposed to flow of oil through high permeable layer, the water takes the path of low permeability(top layer) and reaches the production well(Figs. 4d through 4f). This causes an early breakthrough of water and leaves a considerable unswept zone particularly in middle layer finally results in reduced oil recovery.

3.2 Set 2

In this case, as shown in Fig. 3b, the vertical injection well is perforated in the bottom layer whereas production well is fully perforated. During oil saturation process(Figs. 5a through 5c), it can be observed that most of the injected oil flows through the high permeable layer. The oil front reaches the production well through this high permeability layer much in advance to that of in the low permeability layers. This caused a difficulty in achieving a uniform oil saturation in the sandpack and the flow rate is increased to establish it as mentioned for Set 1. During water flooding, due to perforations in bottom layer, water took the bottom low permeable path and quickly reaches the production well without penetrating in the middle layer(Figs. 5d and 5e) and left most of the reservoir area unswept. A clear layer separation of the front is seen in Fig. 5f. This separation shows the strong resistance to entry of water into the high permeability layer and the reason for this is discussed later.

3.3 Set 3

Figure 3c shows the schematic of the flow model for Case 3. In this case, vertical injection well is perforated in the high permeability layer and production well is fully perforated. During oil saturation, since the injection well is perforated in the middle high permeability layer, oil front took the high permeability path and reached the production well(Figs. 6a through 6c). To achieve uniform oil saturation the flow rate in this case is increased to about 250 ml/hr. During waterflooding, due to well perforation in the high permeability layer, water initially started flowing through the middle layer as shown in Figs. 6d and 6e). Later on, upon continuous water injection, water penetrates in to the bottom low permeability layer and eventually approached the production well leaving major portion of the reservoir unswept(Fig. 6f).

3.4 Set 4

The common observation during waterflooding in experiments of Set 1 to 3 is that injected water preferred the path of low permeability. In order to validate this observation, in this set of experiment, pattern of layers is changed. As observed in Fig. 3d, the top and bottom layer are high permeability layers whereas middle layer is of low permeability. Both the vertical injection and production wells are fully perforated. During oil saturation, it can be observed in Figs. 7a through 7c that oil preferred the path of high permeability as observed in previous cases leaving the low permeable zone unswept. In order to achieve uniform oil saturation in the pack, the flow rate is then increased to 150 ml/hr.

During waterflooding, as the well is fully perforated, water started to flow in the top high permeable layer. However, upon continuous water injection, when it penetrates the middle low permeability layer, it preferably flow through that layer and approached the production well as observed in Figs. 7d through 7f. This condition validated the previous cases where major portion of injected water flows through the low permeability layer.

This behavior during oil flooding and water flooding can be understood by looking into the capillary pressure principle. In this particular case, water and oil are assumed to be wetting and non wetting phases, respectively. The capillary pressure is defined as,

$$p_c = p_o - p_w \qquad (1)$$

where, p_o and p_w are oil and water phase pressures, respectively.

$$p_c = \frac{2\sigma cos\theta}{r} \qquad (2)$$

where, σ is the interfacial tension between oil and water, θ is the contact angle, and r is the radius of curvature. For a sand of constant wettability, θ is constant. Since the pore radii is proportional to the grain size, the capillary pressure in low permeability region (small particles) would be higher than in the high permeability region (large particles). Thus, one can write,

$$p_{c,low} > p_{c,high} \qquad (3)$$

In above equation, subscripts $high$ and low corresponds to high and low permeability layers, respectively. Therefore, capillary pressure in higher in low permeability layer, i.e. $p_{o,low} - p_{w,low} > p_{o,high} - p_{w,high}$. During oil flooding, the pack is filled with water and hence the water phase pressure is approximately the same in both the high and low permeable layer, i.e. $p_{w,low} \approx p_{w,high}$. Hence, the oil phase pressure is higher in low permeability layer, i.e. $p_{o,low} > p_{o,high}$. This causes the oil to flow preferentially through high permeability layer and bypass the low permeability region.

During waterflooding the pack is fully saturated with oil and thus the oil phase pressure is approximately same in both the high and low permeable layers, that is $p_{o,low} \approx p_{o,high}$ and $p_{w,low} < p_{w,high}$. Water is therefore, preferentially flows through the layers of low permeability and bypasses the high permeability region causes an early breakthrough. Above discussion considers the sandpack as water wet media but in case if the sand is oil wet, then the flow phenomena is reversed. In the later case, oil takes the low permeable path during oil flooding and water takes the high permeable path during water flooding.

4 Conclusion

Immiscible water-flood flow visualization experiments have been performed with a well defined permeability heterogeneity. From the present study, the following important conclusions can be drawn.

1. permeability heterogeneity can significantly affect the initial fluid distributions in stratified reservoir.

2. the flow phenomena occurring at low flow rate is capillary pressure dependent. In water wet media, water phase pressure is lower in low permeability layer and hence water follows the low permeable path during waterflooding.

3. the injection well openings (perforations) have a little effect on the flow patterns. Injected water tries to flow through the low permeability layers resulting in an inefficient sweep of high permeability layers.

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Nomenclature

English Letters

p	pressure
r	radius of curvature
S	saturation

Greek Letters

σ	surface tension
θ	contact angle

Subscripts

i	irreducible
c	capillary
o	oil phase
w	water phase
$high$	high permeability layer
low	low permeability layer

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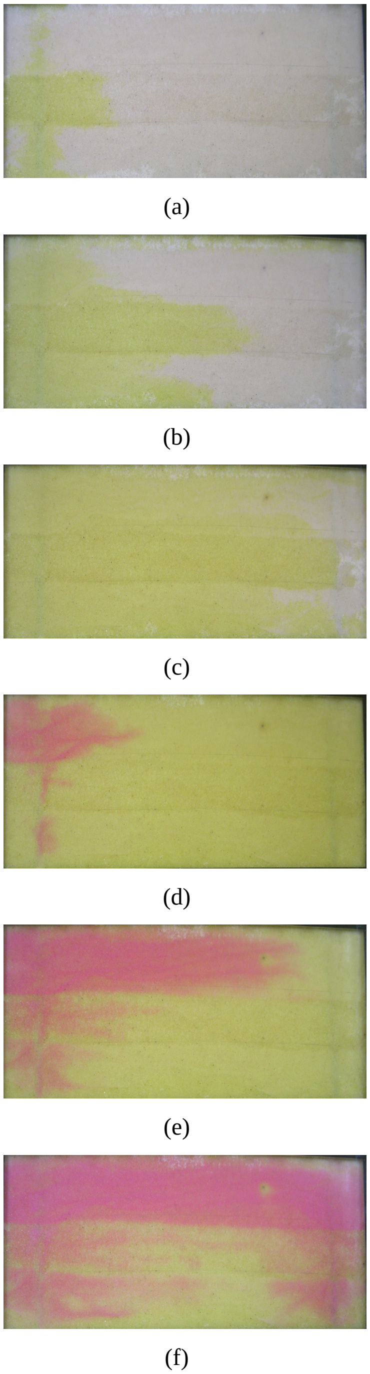

Figure 4: Oil and water flood fronts for Set 1 (Low–High–Low permeability layer configuration). Yellow and red colors indicate oil and water, respectively.

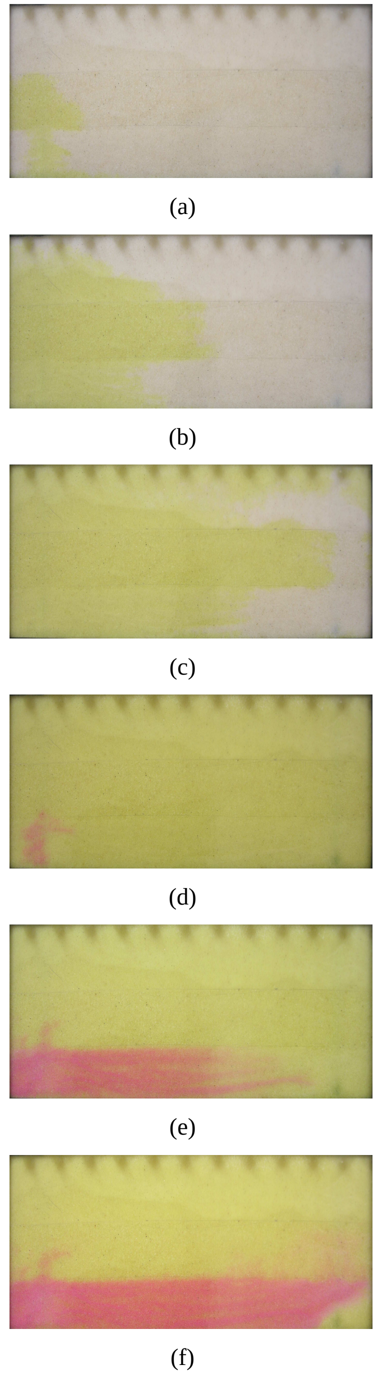

Figure 5: Oil and water flood fronts for Set 2 (Low–High–Low permeability layer configuration). Yellow and red colors indicate oil and water, respectively.

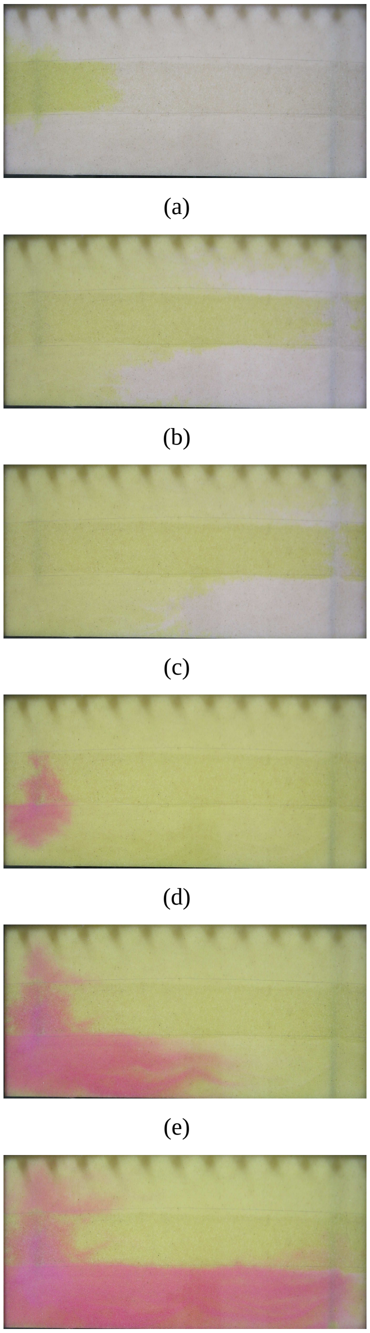

Figure 6: Oil and water flood fronts for Set 3 (Low–High–Low permeability configuration). Yellow and red colors indicate oil and water, respectively.

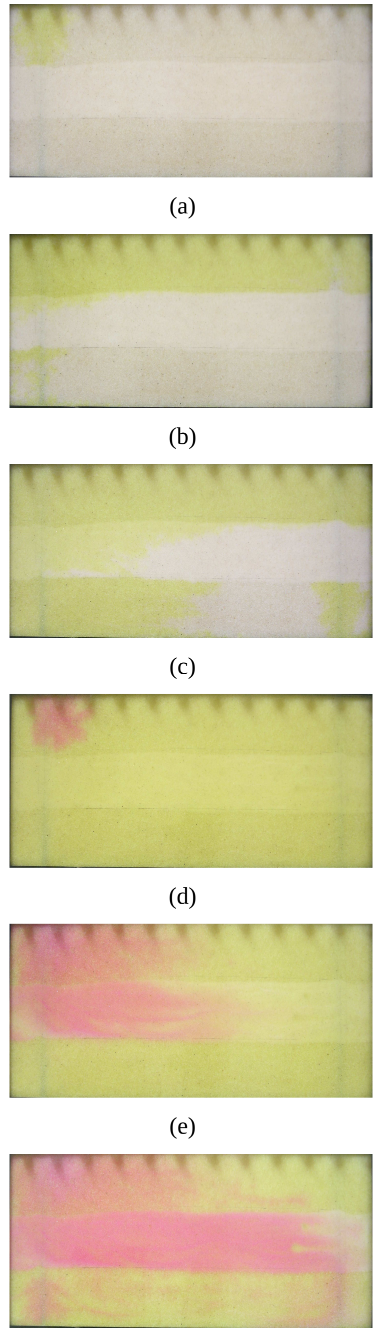

Figure 7: Oil and water flood fronts for Set 4 (High–Low–High permeability layer configuration). Yellow and red colors indicate oil and water, respectively.