AN EXPERIMENTAL STUDY OF WATERFLOODING FROM LAYERED SANDSTONE BY CT SCANNING

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ABSTRACT

In this study a new method is approached by CT scanning apparatus to investigate the fluid crossflow between communicating layers of a heterogeneous sandstone model during the process of waterflooding and its effect on oil recovery due to permeability variation of each layer. The model consists of three communicating sandstone layers with equal thickness. A special coreholder was designed to conduct flow into each individual layer independently and to ensure that the summation of flow rate measured at the outlet end of each individual layer is equal to the flow rate of the whole core. CT scanning technology was approached to trace the development of the saturation profile in the layered model during waterflooding process. Experimental results show that oil recovery of each individual layer is summation of local oil displaced in each individual layer and oil crossflow from neighboring layers. The trend of oil crossflow is mainly from layer with low permeability to that with high permeability. Oil crossflow increases significantly after water breakthrough. Further study shows that oil recovery is enhanced as the permeability variation coefficient of the heterogeneous medium is reduced.

INTRODUCTION

Geological heterogeneity in reservoirs is usually classified into several types, while the layered texture associated to sedimentation process is believed to be the most common one. Heterogeneous characteristics of reservoir may result in several anomalous phenomena when a reservoir is waterflooded, such as fluid crossflow which are mainly due to permeability variations between sedimentary layers.

The phenomenon of fluid crossflow between communicating layers has been observed by many researchers in various experiments [2,4]. Past studies of fluid flow in stratified systems suggested that fluid crossflow between layers may attribute to several factors such as flow rate, oil viscosity, IFT, transverse dispersion and gravity segregation, etc[2]. Effects of viscous forces and pressure distribution of layered model studied by Zapata, *et al.* [3] has been validated by other researchers [1,4]. However, few quantitative experimental results on fluid crossflow between communicating layers and analysis of effluent from layers with different permeability have been reported.

The objective of this study is to establish a new experimental method by measuring the effluent from each layer and at the same time capturing the saturation profile by CT scanning, in order to quantitatively investigate the fluid crossflow between communicating layers of a sandstone model during the process of waterflooding.

EXPERIMENTAL

Core Sample and Fluids

Two groups of water wet YDG sandstone outcrop from Shanxi, China were used for the experiment. The heterogeneous model consists of three communicating sandstone layers with equal thickness but different permeability, which is labeled as high, medium and low permeability. Layer with high permeability is located on top and layer with low permeability in bottom. Petrophysical parameters of the model are listed in Table 1. The refined oil (Caltex White Oil Phamra) with viscosity of 12cP at 25degC was degassed by vacuum. The brine was NaBr solution (CT enhancer) with salinity of 50,000 ppm.

Experiment Set-up and Procedure

The experimental schematic is illustrated in Figure 1. A special material (PEEK) coreholder was used for CT scanning (GE Lightspeed 8) and there are two seals on down steam end stem to seal the "fracture" between two layers, so that the coreholder is to conduct outlet flow from each individual layer independently.

The procedures of coreflood experiment are summarized as following steps. First, each dried single layer model was saturated with brine by vacuum. The model consists of three sandstone layers was loaded into coreholder with 725psi overburden pressure. A tissue was placed between strata to ensure capillary contact. Irreducible water saturation was established by oil displacement at rates from 0.1 to 4.0ml/min (capillary number 2.85E-8 to 1.14E-6). Subsequently, water flooding with injection rate at 1.0ml/min (capillary number 2.85E-7) was conducted into the heterogeneous core until water cut in the core reached 99.9%. The production from each layer was recorded. CT scannings were performed on the core to capture the three stages of the experiment, being dry, after being 100% saturated and after being waterflooded, respectively. Finally, a saturation profile of each layer was derived from each stage of CT scanning. The relative permeability endpoint is 0.103, and it indicates the outcrop sandstone is water-wet.

RESULTS AND DISCUSSION

Saturation Profile of Each Single Layer

It is shown in Figure 2 that the layer with high permeability has steepest water leading front and earliest breakthrough after water flooding due to its high flow rate, large viscous force and small capillary force. After breakthrough, the water saturation profile stops increasing significantly. Meanwhile the leading front is flat for both the medium permeability layer and low permeability layer due to low flow rate, small viscous force and large capillary force in the layers. Water breakthrough from those two layers is more lagged than that from layer with high permeability. However, water saturation profiles in the medium permeability layer and the low permeability layer increase slowly. The uneven distribution of water saturation profile in the low permeability layer is believed to be due to its own heterogeneity.

Calculation of Crossflow between Communicating Layers

Quantitative measurement by volumetric method shows that recovered oil of each individual layer obtained from the outlet end is the summation of local oil displacement in each individual layer and oil crossflow from its neighboring layers. The remaining oil saturation in each layer of the stratified model can be obtained by CT scanning method, from which local oil displacement in each individual layer can be calculated. The oil crossflow between communicating layers is evaluated quantitatively by comparing oil recovered from the outlet end and local oil displaced in each individual layer. For each individual layer, the oil crossflow direction tends to be from its neighboring layers into the layer itself if recovered oil measured by volumetric method is larger than that by CT scanning method. On the other hand, the oil crossflow direction is from the layer itself out to its neighboring layers if the oil recovered by volumetric method is smaller than that by CT scanning method. As shown in Figure 3, the trend of oil crossflow is mainly from layer with lower permeability to that with higher permeability. Oil crossflow increases significantly after water breakthrough.

By assuming water displacement is piston-like, Figure 4 shows oil phase crossflow pattern with viscous force, gravity, capillary force and pressure distribution of each layer of the stratified model at different stage of the water flooding, which can be regarded as an extension of works by Zapata *et al.* [3].

Figure 4a shows the profile of water leading front and pressure distribution at early stage of waterflooding. The water leading front of the high permeability layer propagates fastest, while the low permeability layer's propagates slowest before water breakthrough. A balance point exists between the leading front of the high permeability and medium permeability layers (the vertical dotted line between Layer 1 and Layer 2 in the left plot of Figure 4a and the intersecting point of the normalized pressure distribution of Layer 1 and Layer 2 in the right plot of Figure 4a), where the pressures of two layers are equal. To the left of the balance point, pressure of medium permeability layer is higher than that of high permeability layer, which leads to a pressure gradient along the vertical direction. And with the effect of gravity and capillary force, oil in the medium permeability layer flows into the high permeability layer along the transverse direction perpendicular to the bulk flow, i.e. oil phase crossflow. Similarly, under the exertion of viscous force, gravity, and the capillary force, oil in the low permeability layer flows into the medium permeability layer as well. As a result, oil recovery of the medium permeability layer measured by volumetric method is almost equal to that calculated by CT method, and the medium permeability layer acts as a transition layer. Because of the similar pressure distribution of each layer, a small vertical pressure gradient drives little oil crossflow during this stage.

As shown in Figure 4b, as water breakthrough occurs at high permeability layer, the pressure distribution in this layer evolves into a straight line, which leads to a higher transverse pressure gradient between the high permeability and medium permeability layer than that before water breakthrough. A large amount of oil is driven by this transverse pressure gradient from the low permeability layer into the high permeability layer perpendicular to the bulk flow (Figure 3). Since the medium permeability layer performs as a transition zone, majority of the oil crossflow emigrates from the low permeability layer during this stage.

Pressure distribution of the medium permeability layer also evolves into a straight line with the same slope as that of the high permeability layer once the leading front reaches the outlet (Figure 4c). As a result, the vertical pressure gradient between the high permeability and medium permeability layers approaches to zero. Along with a weak effect of capillary force between the two layers, little oil is driven across between these two layers. At the same time, the vertical pressure gradient between low permeability and medium permeability layers becomes larger. With the effect of gravity and capillary force, oil in low permeability layer trends to flow into medium permeability layer in the transverse direction perpendicular to the bulk flow, which is the main reason that oil recovery from the medium permeability layer measured by volumetric method increases significantly while that by the CT method remains the same after 1 pore volume is injected (Figure 3).

Effect of Permeability Variation Coefficient on Oil Recovery

As shown in Figure 5, the Permeability Variation Coefficient (V_k the ratio of permeability standard deviation and average permeability) affects oil recovery of the stratified heterogeneous models during waterflooding process. The oil recovery from model with lower V_k (Group 2) is greater than that with higher V_k (Group 1) due to strong heterogeneity on model with higher V_k (Group 1). The trend is more obvious when pore volume injected is less than 1.5 PV. Oil recoveries from two sets of stratified heterogeneous model saturates to the same values as cut reaches 99.9%.

CONCLUSION

Profile of water saturation in each layer of a model is obtained by CT scanning method. The profile can clearly describes the tendency of leading front in each layer.

A new method is established to investigate the fluid crossflow quantitatively between communicating layers of a heterogeneous sandstone model during waterflooding. The trend of oil crossflow is mainly from layer with low permeability to that with high permeability. Oil crossflow increases significantly after water breakthrough.

The Permeability Variation Coefficient (Vk) affects oil recovery of the stratified heterogeneous models. Oil recovery increases as the permeability variation coefficient of the heterogeneous medium is reduced.

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Table 1. Petrophysical Parameters of Core Samples

Group No.	Sample No.	Length L	Width W	Height H	Porosity Φ	Perm. Ka	Vk	Perm. ratio Jk
		cm	cm	cm	%	mD		
1	2-11-5	14.99	4.42	1.53	23.1	1188	0.71	7
	3-5-4	15.02	4.46	1.44	25.6	441		
	3-14-2	15.03	4.48	1.41	25.9	176		
2	2-11-2	14.96	4.44	1.47	23.6	1266	0.45	3
	3-2-7	14.97	4.46	1.42	23.5	808		
	3-5-2	14.91	4.42	1.47	25.8	375		

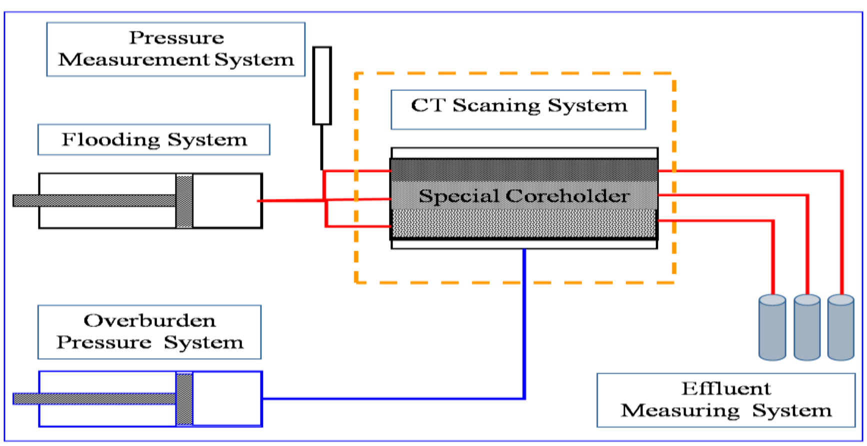


Figure 1. Schematic of water flooding test for layered sandstone model

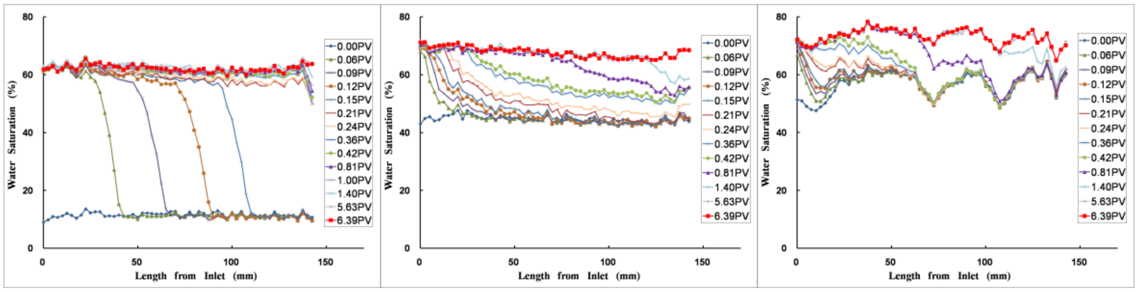


Figure 2a. Figure 2b Figure 2c.

Figure 2. water saturation profile of each layer for model group 1 vs. pore volume injected

The three plot of figure 2 are high permeability layer, medium permeability layer, and low permeability layer from left to right in turn.

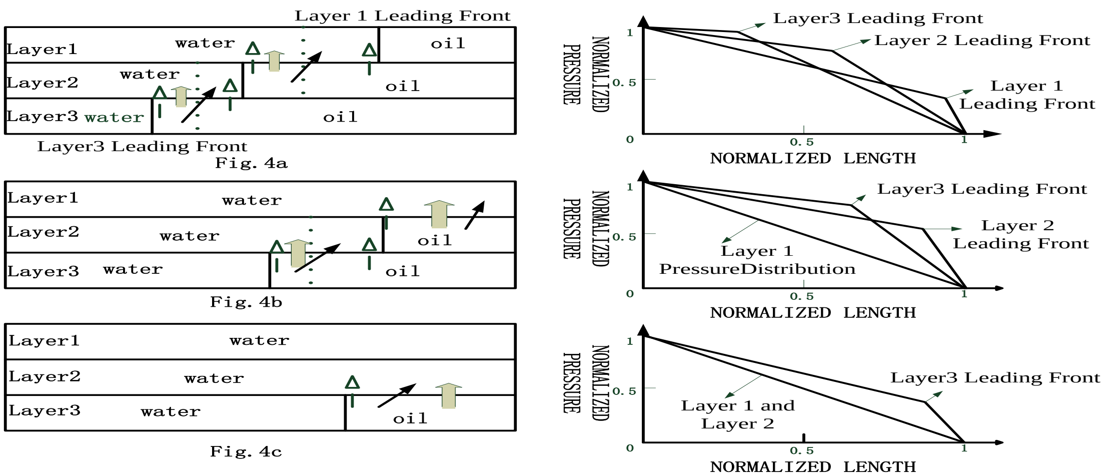
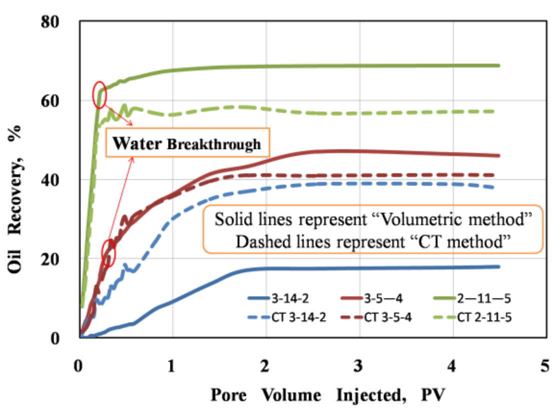


Figure 4. Conceptual picture of oil crossflow pattern(left) and pressure distribution (right) of layered heterogeneity model. Double arrow represents viscous crossflow, single solid arrow represents gravity crossflow, and the dashed arrow represents capillary crossflow.



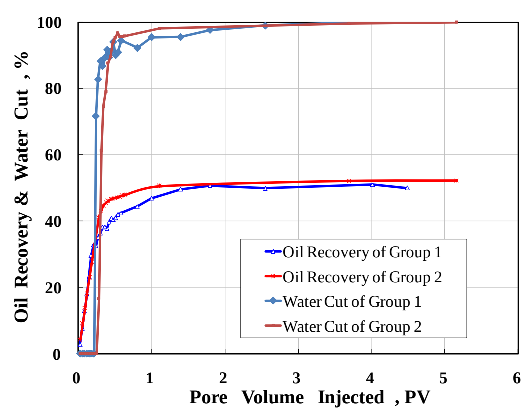


Figure 3. Oil recovery by volumetric/CT method for group1 vs. pore volume injected

Figure 5. Oil recovery and water cut vs. pore volume injected