Experimental Investigation of Factors Influencing Remaining Oil Distribution under Water Flooding in a 2-D Visualized Cross-Section Model

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ABSTRACT: About 70% of the remaining oil remains underground after water flooding, and there is a need to better understand the formation and distribution of this remaining macroscopic oil to enhance oil recovery. In this study, three types of visual plate models were devised with different packing sequences: homogeneous (J), high-permeability layer on top (F), and low-permeability layer on top (Z). Based on these models, several visual flooding experiments were conducted to study the water flooding physics and the remaining oil distribution pattern of an offshore thick heavy oil reservoir under the impact of formation heterogeneity, packing sequence, model length, and permeability contrast during water flooding. These displacements were monitored photographically, and the effluent production profiles were recorded. The results showed that layer permeability and gravitational segregation play an important role during the water flooding process in layered porous media. Experimental results based on the model with different lengths show that the breakthrough oil recovery decreases with the increase of well spacing. Finally, a correction was made to the gravity number by introducing a scaling factor that characterized the formation heterogeneity and packing sequence in thick formation, compared to a known gravity number; the modified gravity number showed a better correlation with breakthrough oil recovery of water and polymer flooding. The research results provide effective guidance for the remaining oil distribution and injection and production parameter optimization in actual reservoirs.

1. INTRODUCTION

Characterization of remaining oil distribution after water and polymer flooding in layered formations, especially for varying injection—production well spacing in heterogeneous systems, is neither straightforward nor well understood. Heterogeneity needs to be properly considered when making the development plan of an oilfield. Flow behavior in heterogeneous media can be understood by laboratory visual models constructed with well-defined heterogeneity. Layered systems with permeability heterogeneity at the reservoir scale have been studied by numerical simulation.1-4 A physical experiment and a numerical simulation method are generally adopted to study the flooding problem of heterogeneous reservoirs. Experimental studies generally use parallel cores and sand packs for simulation.5-15 However, this method ignores the important role of gravitational segregation in high-permeability reservoirs, which is quite different from the actual oil—water flow in the reservoirs.

A systematic experimental investigation was conducted by Craig16 to study the effect of gravity segregation, injection rate, and stratification on water flooding performance. Experimental results of the abovementioned study showed a good correlation of breakthrough oil recovery with the scaling group, which has the dimensional form of the ratio of horizontal to vertical pressure differentials. Roti17 performed an experiment on cross-bedded glass bead packs to study the effects of the layer thickness and permeability contrast on fluid flow. It was concluded in the above study that the breakthrough recovery decreases with an increase in the permeability contrast. Cinar18 quantified the transition between the capillary, viscous, and gravity forces through visualization experiments and numerical simulation. McDougall and Sorbie19 performed numerical simulations to evaluate the effect of capillary pressure and viscous forces on the displacement efficiency, and they found that the flooding efficiency tends to increase when the viscous forces become more dominant in a layered water-wet medium. Weber20
Table 1. Model Number and Parameters

| model | length × width (cm) | layer height (cm) | packing sequence | permeability (mD) | permeability contrast | porosity |
|-------|---------------------|------------------|-----------------|------------------|----------------------|----------|
| J1    | 28 × 8              | 8                | homogeneous     | 500              | 1                    | 0.353    |
| J2    | 28 × 8              | 8                | homogeneous     | 1500             | 1                    | 0.363    |
| J3    | 28 × 8              | 8                | homogeneous     | 2800             | 1                    | 0.347    |
| J4    | 50 × 8              | 8                | homogeneous     | 1500             | 1                    | 0.321    |
| Z1    | 28 × 8              | 2/3/3            | fine upward     | 600/1300/1900    | 3.16                 | 0.328    |
| Z2    | 50 × 8              | 2/3/3            | fine upward     | 600/1300/1900    | 3.16                 | 0.351    |
| F1    | 28 × 8              | 3/3/2            | coarse upward   | 2400/1500/800    | 3                    | 0.316    |
| F2    | 50 × 8              | 3/3/2            | coarse upward   | 2400/1500/800    | 3                    | 0.326    |
| F3    | 50 × 8              | 3/3/2            | coarse upward   | 3500/2000/700    | 5                    | 0.365    |

Conducted water flooding experiments through a dimensionally scaled model to investigate the effect of the rate on oil recovery. Meanwhile, some researchers conducted a micromodel displacement experiment to investigate the effect of pore morphology and size on the displacement mechanism. According to the presented review, it can be concluded that there have been very few reported studies regarding the effect of permeability, model length, and permeability contrast on the water and polymer displacement efficiency in layered porous media with the consideration of gravity segregation.

This paper conducted several visual flooding experiments to describe fluid flow in layered porous media, and the effect of the permeability contrast and the packing sequence on water and polymer flooding performance was investigated. A scaling factor that characterized the effect of the permeability contrast and the packing sequence on water flooding in layered formation was introduced. The modified gravity number was proposed to quantify the correlation of these factors with the water and polymer displacement effect. Acquiring a better understanding of the relationship between the packing sequence and the permeability contrast of the layered porous media and the water displacement process is vital in predicting water flooding performance.

2. EXPERIMENTAL SETUP

2.1. Model Design. Three types of models were designed with different packing sequences. The specific parameters of the models are shown in Table 1. All models have a thickness of 0.45 cm and a total height of 8 cm, and a varying layer height was designed according to the packing sequence of the model. The permeabilities of the individual layers were measured via separate homogeneous packs of relevant glass beads.

Underground realistic porous media were composed of solid grains and cement material, similar to which a different permeability layer in our model was made of glass beads with different sizes. In addition, an epoxy resin was used to cement the glass beads together. The model permeability was affected by the amount of resin used, and a low-permeability pack was obtained with more resin used because the degree of cementation was higher. Numerous glass bead packs were made based on which, the air permeability was measured; then, the relationship of the layer permeability with the glass bead size and the mass ratio of the resin is obtained. Finally, the model permeability was controlled by adjusting the bead size and the mass ratio of the resin. Different permeability models were achieved by adding different mass ratios of the epoxy resin. The procedure is as follows: ① A glass bead with a mesh size range from 75 to 320 was selected and weighed; ② according to the weight of the selected glass bead, a specified amount of resin was weighed, and in our model, the weight percentages of the added resin ratio were 7, 10, and 15%; ③ a target glass bead used for the plate model by mixing the bead size and the resin was prepared; and ④ a sand pack model was made, and the permeability measurement of the sand pack was conducted. The results are shown in Figure 1.

![Figure 1. Air permeability of the sand pack with different combinations of the mesh size and the resin ratio.](https://doi.org/10.1021/acsomega.0c05534)

To investigate whether the packs and layers have the same permeability, we made a plate model with a mesh size of 200 and a resin ratio of 10% as used in the sand pack; the schematic of the permeability measurement experiment of the plate model is shown in Figure 2. The measured permeability was 1913 mD compared to 1806 mD of the sand pack model, and the relative error of 6% indicates that the measured permeabilities of both models show good consistency.

Two boxes of glass plates with bulk volumes of 100.8 cm³ (28 × 8 × 0.45 cm³) for the short model and 180 cm³ (50 × 8 × 0.45 cm³) for the long model were initially built. Glass beads of different sizes were packed into a box to obtain a layer height as shown in Table 1. The model setup consists of a
visual cross-section model vertically placed on a platform. It comprises a camera with a video recording system, a pressure transducer, and an ISCO pump.

A high-quality camera was employed in the experiment to visualize the flooding process in real-time, and displacement effects can be demonstrated using translucent packs of glass beads and a dyed experimental fluid to indicate the displacement fronts. The schematic of the visual model used in this study is shown in Figure 3. Glass beads were used to build a two-dimensional (2-D), layered flow model. The model we used for the displacement experiment was made of perspex in a 2-D structure. The transparent Perspex material used has excellent optical properties, permitting visualization of fluid movement within the models. This material is commonly used in flooding experiments for the convenience of visualizing the flooding process.25–29

The experimental model in this paper considers three modes of heterogeneity, homogeneous model (J), fine upward model (Z), and coarse upward model (F), in which the model F has two permeability contrasts of 3 and 5. The effects of permeability and injection—production well spacing on remaining oil distribution during water flooding are considered.

2.2. Test Fluids and Experiment Procedure. Test fluids: The water phase is prepared according to the water ion composition of the formation water with a salinity of 8878 mg/L, and the water phase density is 1.03 g/cm³ with a viscosity of 0.92 mPa·s at 25 °C. The simulated oil is prepared by mixing vacuum pump oil and kerosene in a volume ratio of 2:1, and the oil phase is dyed with Sudan red to facilitate our observation during fluid flow, which had a density of 0.87 g/cm³ and a viscosity of 19.8 mPa·s at 25 °C. The polymer solution adopts the formation water and the polymer used in the L oilfield; the concentration is 600 mg/L with a viscosity of 7.2 mPa·s.

The experimental process is as follows: ① According to measured permeability data in Figure 1, the mesh size of the glass bead and the ratio of the epoxy resin were adjusted to achieve the control of the permeability of different layers, and a cross-section plate model with different packing sequences and permeability contrasts was made. ② The experiment process was connected as shown in Figure 4. ③ The oil displacement experiment was conducted according to the experimental parameters presented in Table 1, and the fluid production data and fluid distribution were recorded at different times until the end of the experiment. ④ The model was cleaned and dried after the experiment. Then, the experimental model and fluid were replaced, and steps ②–④ were repeated.

A visual flooding experiment was conducted under two injection schemes. Water flooding: the formation water is used as the displacement fluid after the model is saturated with oil, and water is injected until the water cut at the outlet reaches 98%. Polymer flooding: water is flooded till the water cut at the outlet reaches 30%, followed by switching to polymer flooding until the water cut at the outlet reaches 98%.

3. RESULTS AND DISCUSSION

3.1. Effect of Permeability on Remaining Oil Distribution. To better illustrate the remaining oil distribution pattern, all of the monitored photographs after complete water flooding were processed through an image processing toolbox in Matlab, the water injected pore volume when displacement process finished was recorded and marked beside each figure. Taking the homogeneous model as an example, the distribution of remaining oil after water flooding in different permeability models is shown in Figure 5. The red phase means oil, the blue dashed line is the front edge of the water, and the direction of water flooding is from left to right.

The viscous pressure difference between injection and production well causes a horizontal flow of water, and the action of gravitational segregation causes the water to flow downward. The permeability of model J1 is 500 mD, and the viscous resistance of the oil—water flow is large compared with models J2 and J3 with the permeabilities of 1500 and 2800 mD, respectively; thus, the fluid segregation phenomenon is relatively weak in model J1, and the injected water has more time to sweep the oil distributed at the upper part of the layered model. Finally, the vertical sweep efficiency of J1 is high with a small amount of residual oil. As the permeability increases (such as the J3 model), the viscous resistance of the oil—water flow decreases, and the fluid segregation phenomenon due to the density difference between injected water and oil is obvious. The bottom part of the model was flushed completely after the water flood finished, resulting in a large amount of remaining oil in the upper area near the production well. At the same time, the flooding caused a large amount of water flow at the lower part of the J3 model, the oil displacement efficiency was high, and the remaining oil saturation was significantly lower than that of the J1 model. As for the model J4, which has the same permeability as J2, as the injection—production well spacing increases, more time is needed for injection water to flow to the production well, and the action of gravitational segregation aggravated, resulting in J4 being more flooded than J2.

3.2. Effect of the Packing Sequence on Remaining Oil Distribution. Taking the fine upward model (Z1) and the coarse upward model (F1) as examples, the distribution of remaining oil after water flooding is shown in Figure 6. A gravity tongue was clearly shown in Z1 due to the combined action of viscous pressure drop and gravity segregation. The overall sweep efficiency of Z1 was low with a large part of the area unswept at the top layer near the production well.
remaining oil distribution map shows that model F1 has a better sweep efficiency than Z1, and when the water preferentially enters the top high-permeability layer with low viscous resistance, the simultaneous vertical flow caused by gravity segregation makes the lower part of the model swept, which leads to a better vertical sweep efficiency.

The remaining oil distribution of the long models Z2 and F2 shows that a severe gravity underride phenomenon was observed in the Z2 model within a high-permeability layer. The remaining oil distribution of the long model F2 after water flooding indicates a different pattern with F1, and we can see that the unswept area occurs with the increase in the model length, due to the interaction of horizontal viscous force and vertical gravity force exerted on fluid flow.

As shown in Figure 7, the injected water breaks through along the top high-permeability layer, which leads to water flooding, and the remaining oil in the middle and bottom layers remains almost unswept. It shows that when the permeability contrast of the layered porous media increases to $S$, the flow of oil and water in the model is mainly controlled...
by the permeability contrast, and the action of gravity segregation is relatively weak, which is obviously different from the F2 model. To summarize, factors such as permeability contrast, gravity segregation, and packing sequence affect the fluid flow and the remaining oil distribution.

3.3. Dimensionless Gravity Number. There are many factors that affect the water flooding process in thick oil reservoirs, such as formation heterogeneity, injection, production well control parameters, and fluid properties. Many scholars combined the dimensionless similar groups analysis and numerical simulation technique to analyze the influence of gravity force, driving force, and capillary force on the flooding law and gave some qualitative understanding of the law, but still lack quantitative mechanism analysis. No analysis and numerical simulation technique to analyze the remaining oil production well control parameters, and factors that affect the effect of gravity segregation and permeability contrast, gravity segregation, and packing sequence affect the fluid flow and the remaining oil distribution.

3.3.1. Homogeneous Formation. Gravitational segregation is caused by the coexistence of horizontal and vertical water flow. When the vertical seepage velocity is large, it is easy to cause flooding at the bottom part of the reservoir.

For a homogeneous reservoir, according to the Darcy formula, the flow velocity in the horizontal direction during water flooding is

\[ v_h = \frac{Q}{A} = \frac{k_x \Delta P}{\mu L} \]  

(1)

where \( \Delta P \) is the displacement pressure difference, kPa; \( L \) is the model length, cm; \( k_x \) is the horizontal permeability, mD; and \( \mu \) is the fluid viscosity, mPa·s. Meanwhile, the vertical flow velocity of water under the gravitational segregation induced by the density difference of water and oil is

\[ v_z = \frac{Q}{A} = \frac{k_z g (\rho_o - \rho_w)}{\mu} = \frac{k_z \Delta \rho g}{\mu} \]  

(2)

where \( k_z \) is the vertical permeability, mD; \( \Delta \rho \) is the density difference of oil and water, g/cm³; and \( g \) is gravitational acceleration, m/s².

3.3.2. Heterogeneous Formation. The heterogeneous model has layer permeability difference. According to the previous experimental results, it can be seen that the permeability contrast has an impact on the remaining oil distribution. Under the same permeability contrast, the injected water breaks through quickly along the bottom high-permeability layer of the Z model due to the combined action of gravitational segregation and permeability heterogeneity. For model F with the high-permeability layer distributed on the top, the injected water preferentially flows along the top high-permeability layer. To some extent, the effect of gravitational segregation is suppressed. The volumetric sweep efficiency of the F model is higher than that of the Z model.

Two dimensionless groups were proposed by Zhou and Tchelepi to identity dominant flow regions at various conditions, which were later validated by Cinar’s experimental results. The two groups are given as

\[ N_{gw} = \frac{\Delta \rho g L k_x}{H \mu_d} \]  

(3)

\[ R_i^2 = \left( \frac{L}{H} \right)^2 \frac{k_x}{k_z} \]  

(4)

where \( v \) is the Darcy velocity, \( \mu_d \) is the displaced phase viscosity, \( N_{gw} \) characteristic time ratios for fluid to flow in the transverse direction due to gravity to that in the horizontal direction due to viscous forces. \( R_i^2 \) is called the effective shape factor, which represents the relative flow capacities of the medium in vertical and horizontal directions.

Substituting eq 1 into eq 3, the gravity number \( N_{gw} \) is derived as

\[ N_{gw} = \frac{k_z \Delta \rho g L^2}{k_x PH} \]  

(5)

where \( k_x \) and \( k_z \) are the average horizontal and vertical permeabilities of the reservoir, \( k_x = \sum k_{h_i} / k_{h_i} \), \( k_z = \sum h_i / k_z \). As we know, water saturation constantly changes during the two phase displacement process, which influences the oil and water phase permeabilities, the \( k_x \) and \( k_z \) values used in the equation are the effective permeabilities of the plate model, and we did not consider the effect of phase saturation for simplicity.

As shown in eq 5, gravity dominates the fluid flow in the long thin reservoir with a low injection rate. To achieve better sweep efficiency, it is the key to ensure that the water injection advances uniformly along each layer and minimizes the water flooding degree caused by gravitational segregation.

From eq 5, we can see that the effect of the packing sequence and the permeability contrast on fluid flow was not fully characterized. Here, we modify eq 5 by introducing a scaling factor \( \alpha \)

\[ \alpha = 1 / \left( J_k + \beta_k \right) \]  

(6)

where \( J_k \) and \( \beta_k \) are parameters that characterize the degree of heterogeneity of layered formation, \( \beta_k = k_{\text{min}} / k_{\text{max}} \), \( J_k = k_{\text{max}} / k_{\text{min}} \). \( \epsilon \) is a constant that indicates the order of the layer packing sequence \( (\epsilon = 1, 0, -1 \text{ with fine upward, homogeneous, and coarse upward formation, respectively}) \), and the physical meaning of which is that both the gravity segregation and heterogeneity

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Figure 7. Remaining oil distribution of model F3 when water flooding finished.
aggregate the water channeling in the formation with a fine upward packing sequence \((c = 1)\), thus leading to a poor flooding performance; however, the water channeling effect was increased in the formation with a coarse upward packing sequence \((c = -1)\); then, a modified gravity number \(N_{pv}\) was derived as eq 7.

\[
N_{pv} = \alpha^* \frac{1}{N_{gv}} = \frac{k_c \Delta P H}{(k_{sc} + \beta_c k_c) \Delta \rho g L^2}
\]  

\(N_{pv}\) characteristic the time ratios for fluid to flow in the horizontal direction due to viscous forces to that in the transverse direction due to gravity.

### 3.4. Comparison Analysis of Dimensionless Numbers \(N_{gv}\) and \(N_{pv}\)

Flooding experiments of water flooding and polymer flooding were conducted based on the above models, and the data of recovery factors and displacement pressure difference under different injection schemes were obtained, which are shown in Table 2. The correlation curve between \(N_{gv}\), \(N_{pv}\) and breakthrough water and polymer flooding recovery factors is shown in Figure 8.

| model | injection scheme | injection rate \((\text{mL/min})\) | pressure difference \((\text{kPa})\) | \(N_{gv}\) | \(N_{pv}\) | recovery factor at water breakthrough \(\%\) | recovery factor of polymer flooding \(\%\) |
|-------|------------------|-----------------------------------|----------------------------------|---------|--------|-----------------------------|-----------------------------|
| J1    | WF\(^a\)         | 0.5                               | 35.5                             | 17.97   | 8.98   | 38.56                       |                            |
| J2    |                  | 0.5                               | 16.8                             | 8.50    | 4.25   | 29.96                       |                            |
| J3    |                  | 0.5                               | 6.6                              | 3.82    | 1.91   | 21.71                       |                            |
| J4    |                  | 0.3                               | 8.2                              | 1.49    | 0.74   | 22.66                       |                            |
| Z1    |                  | 0.3                               | 6.1                              | 1.37    | 0.23   | 14.91                       |                            |
| Z2    |                  | 0.6                               | 25.6                             | 5.75    | 0.99   | 20.7                        |                            |
| F1    |                  | 0.3                               | 10.2                             | 2.21    | 1.19   | 26.91                       |                            |
| F2    |                  | 0.3                               | 9.5                              | 2.59    | 0.55   | 17.56                       |                            |
| J1    | PF\(^a\)         | 0.5                               | 80                               | 40.49   | 20.25  | 56.15                       |                            |
| J2    |                  | 0.5                               | 45.7                             | 23.13   | 11.57  | 52.62                       |                            |
| J3    |                  | 0.5                               | 13.5                             | 7.81    | 3.90   | 46.02                       |                            |
| J4    |                  | 0.3                               | 14                               | 2.54    | 1.27   | 30.71                       |                            |
| Z1    |                  | 0.3                               | 7.2                              | 1.62    | 0.28   | 23.57                       |                            |
| Z2    |                  | 0.6                               | 18.4                             | 4.13    | 0.71   | 28.11                       |                            |
| F1    |                  | 0.3                               | 9.5                              | 2.06    | 1.10   | 27.87                       |                            |
| F2    |                  | 0.3                               | 9.9                              | 2.69    | 0.57   | 23.45                       |                            |

\(^a\)WF: water flooding; PF: polymer flooding.

It can be seen from Figure 8 that with the increase of the dimensionless numbers, the breakthrough recovery factors of water and polymer flooding gradually increase. The reason is that with the increase of \(N_{pv}\), the effect of driving force on fluid flow is more pronounced than gravity force. The longitudinal flooding due to gravitational segregation is weak, and the injected water flows more uniformly in each layer of the formation, which has a better sweep efficiency.

At the same time, as shown in the correlation curve, the regression coefficient values of \(N_{gv}\) with breakthrough water and polymer oil recovery were 0.63 and 0.92, respectively. However, the regression coefficient values of \(N_{pv}\) after the scaling factor \(\alpha\) was introduced can be up to 0.87 and 0.96, respectively. The proposed dimensionless number \(N_{pv}\) was validated by the experimental results, which can be used to better characterize the water and polymer flooding performances in layered formation.

### 4. CONCLUSIONS

In this work, a flow visualization study has been carried out to investigate the effect of permeability, packing sequence, and
permeability contrast on remaining oil distribution of water and polymer flooding in layered porous media.

For the homogeneous model, the remaining oil distribution and sweep efficiency vary with the permeability. Gravitational segregation plays an important role in the high-permeability formation due to small vertical viscous resistance, which leads to water flushing in the bottom part of the formation, with remaining oil distributed in the upper and middle parts.

For the heterogeneous model, formation with a high-permeability layer on the top is more beneficial for the fluid flow along the upper part, which suppresses the gravitational segregation effect effectively; thus, the water sweep efficiency of the coarse upward model is better than that of the fine upward model.

Direct scaling of immiscible displacements from physical models or cores to reservoirs may not be valid because packing sequences are different, especially in heterogeneous media with high-permeability contrast. A scaling factor that characterizes packing sequence and permeability contrast of layered porous media was proposed. The breakthrough oil recovery of water and polymer flooding fits well with the modified N_F. Therefore, the derived correlation equation may be used to predict the water and polymer flooding performance under layered formation with different geological properties.

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**Notes**

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