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Experiments of Water Flooded Longitudinal State on Offshore Thick Reservoir

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Abstract

Reservoir sedimentary rhythmic is an important geological factors influencing the dynamic characteristics of the reservoir development and residual oil distribution. Bohai LD oil field is a typical thick reservoir, large well spacing multilayer commingled production in offshore oil field conditions, the gravity effect is more apparent, the remaining oil in the middle and high water period is comparatively complicated. For further study the remaining oil distribution of reservoir after water flooding, the research of indoor core displacement experiment was carried out. Combine the reservoir properties, design parameters according to similar principle, in this paper, the distribution of remaining oil and the production dynamics characteristics under different rhythm is researched. The research results indicate that: Due to gravitational differentiation, the reservoir is submerged at the bottom under homogeneous rhythm. The higher the core permeability, the stronger the gravity differentiation act, the smaller water flooded vertical thickness is, and remaining oil concentrate at the top. Gravity makes positive rhythm formation longitudinal contradictions become more prominent, after water flooding breakthrough, water cut rise fast, core recovery is low, the remaining oil is concentrated in the upper part of the low permeable formation; Gravitational differentiation can play a role in reverse rhythm, water drive is relatively uniform, core recovery is high. Under composite rhythm, the displacement situation of water drive is similar to the single rhythm.

Key words: Thick oil layer; Residual oil distribution; Sedimentary rhythm; Physical experiment

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INTRODUCTION

The remaining oil distribution research is the key of the oil field development, which is mainly affected by reservoir sedimentary characteristics and development factors.[1-4] For water flooding development oilfield, laboratory experiments and field practices showed that the existence of the vertical heterogeneity reservoir, makes the injection water monolayer onrush, serious interlayer interference, the degree of vertical layers use differences; Under the condition of multilayer commingled production, interlayer interference phenomenon is more prominent in offshore oil field.[5] Reasonable formation division, horizontal well products from potential single layer, a lot of measures such as water plugging, profile control, are major means of improving oilfield development effect.[6-8] For thick oil layer, gravity drive mode has become a very important influence water drive effect and affects residual oil distribution.[9-10] LD offshore oil field is a typical thick reservoir, under the condition of large well spacing for offshore oil field development, gravity is more outstanding, in view of the geological characteristics of LD oil fields, from the field in the well group to select several typical heterogeneous reservoir, a typical model is established according to the similarity principle, carried out indoor core displacement experiment, simulated oilfield water flooding development process, know the remaining oil distribution law, provide good basis for oilfield adjustment exploration.

1. OILFIELD SURVEY

LD oilfield is a typical thick reservoir which belongs to delta front deposits. When the single well is drilled, the thickness of the reservoir is up to 60 m and the thickness of the layer is greater than 25 m. The heterogeneity reservoir is serious, which is characterized by high porosity and high permeability (the porosity is 24% -33% and the permeability is 200-3000 mD). Formation crude oil is conventional crude oil whose viscosity is 17 mPa·s and density is 0.87 g/cm^3. LD oilfield was put into operation in 2005. By the end of 2016, the comprehensive water cut of the oilfield was less than 80%, and the recovery degree was close to 30%.

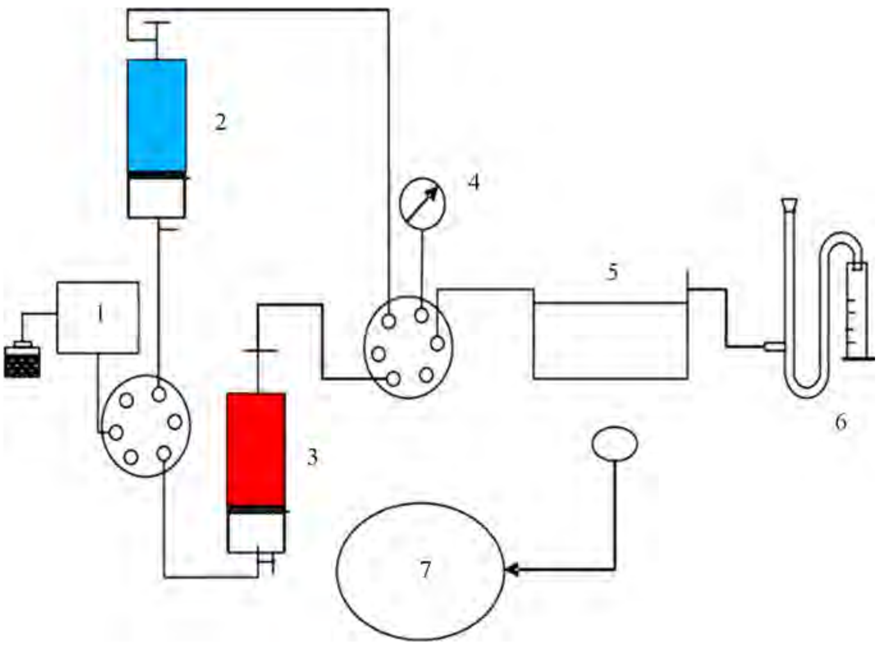
2. EXPERIMENT PREPARATION

2.1 Experiment Material

The experiment materials are mainly include: (a) The flat model is made of artificial core, specification for 28.0 cm×0.45 cm×7.0 cm (length × width × height). (b) The formation water is simulated by the experimental water that mixed with the ion composition of water source wells in LD Oilfield. The total salinity is 8878 mg/L. The saline water viscosity is 0.92 mPa·s at 25℃. (c) The experimental oil whose viscosity is 19.8 mPa·s at 25℃ is vacuum pump oil mixed kerosene by volume ratio 2:1. In order to facilitate the observation during the experiment, the simulated oil was added to the proper amount of Sultan four, and the simulated oil was dyed red. (d) Experimental temperature is at 25℃.

2.2 Experiment Equipment and Process

The visual experiment device consists of flat pump, intermediate container, six way valves, high precision pressure gauge, oil-water separator and image acquisition system (Figure 1). In order to make the effect more obviously, water turns blue by adding methyl blue while oil turns red by adding Sultan four.



1-pump; 2-colored water; 3-colored oil; 4-pressure gage; 5-core holder; 6-oil-water measurement; 7- image acquisition system

Figure 1
Visualizing Experimental Devices and Processes

2.3 Experiment Procedure

The main steps of the experiment are: (a) According to the experimental design requirements, kinds of flat models with different sedimentary rhythms are made out. (b) Eeighing dry weight, Saturating analog oil by pumping model, measuring porosity. (c) Connect the piping in accordance with the experimental procedure. Water flooding is taking by 0.5 mL/min of injection rate. When the injected water enters the wellhead of the plate model, zero time is set. Record injection pressure, cumulative output oil volume, cumulative injection volume, and water breakthrough time until water cut is more than 98%. During the experiment, the images are collected continuously. (d) Replace flat model, repeat (a)-(c).

3. THE RESULT AND THE ANALYSIS OF EXPERIMENT

3.1 Homogeneous Rhythm Formation

3.1.1 Base Parameter of the Formation Model

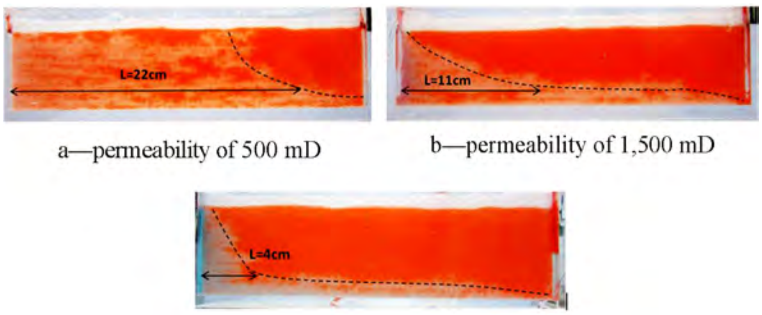
There are 3 groups experiment for homogeneous rhythm formation, the permeability of 3 models are 500, 1,500 and 2,800 mD respectively, the length, height and thickness are 28.0, 7.0 and 0.45 cm respectively, the parameters of homogeneous formation model shows in Table 1.

Table 1
Experiment Parameters of the Homogeneous Formation Model

Model number	Permeability /mD	Net weight /g	Wet weight /g	Porosity /%	Saturated oil /mL	Displacement pressure /KPa
1	500	455.9	487.3	35.3	31.1	36.4
2	1,500	469.6	501.6	36.3	32.0	17.2
3	2,800	467.2	501.7	34.7	35.0	7.3

3.1.2 The Comparison of Experimental Result

(a) The characteristics of oil-water distribution when water flooding breakthrough



a—permeability of 500 mD
b—permeability of 1,500 mD
c—permeability of 2,800 mD

Figure 2
Different Permeability Homogeneous Formation Model Oil-Water Distribution on Water Breakthrough Time

The comparison of oil-water distribution between 3 formation models that of different permeability (Figure 2) shows that: Due to gravity differentiation the bottom is submerged first when water breakthrough, the higher core permeability, the less distance of the transition point of the front of oil-water and injection side. The gravity differentiation is determined by the seepage speed of horizontal and vertical direction, the horizontal seepage speed is expressed as:

$$V_{\text{horizontal}} = \frac{K_{\text{horizontal}}}{\mu} \cdot \frac{\Delta P}{l} . \quad (1)$$

Vertical seepage speed effect by the gravity differentiation of water and oil:

$$V_{\text{vertical}} = \frac{K_{\text{vertical}} g\ (\rho_w - \rho_o)}{\mu} . \quad (2)$$

When the seepage speed that of horizontal is equal with that of vertical, the Equation (1) divide Equation (2):

$$\frac{V_{\text{horizontal}}}{V_{\text{vertical}}} = \frac{\Delta \rho g l}{\Delta P} = N_g . \quad (3)$$

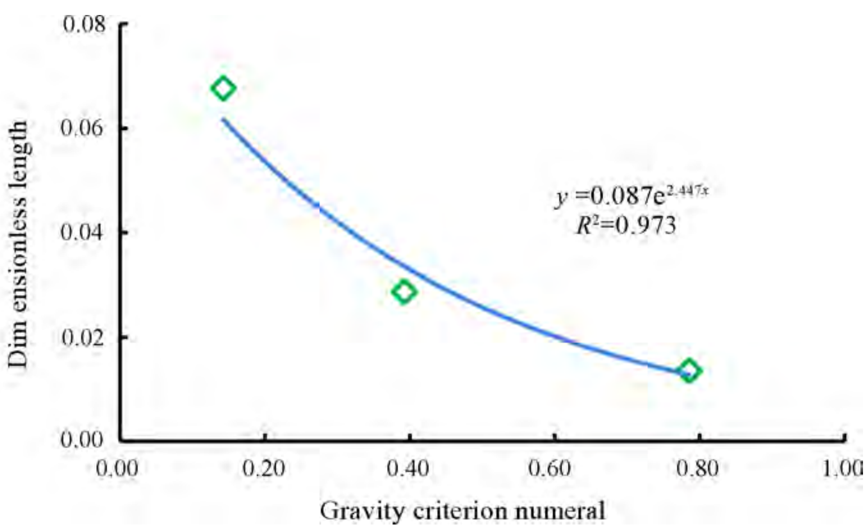


Figure 3
Gravity Criterion Numeral and Dimensionless Length Relationship Curve

That define N_g as gravity criterion numeral, the physical meaning is the ratio of gravity gradient and differential pressure gradient of displacement, in addition, that define L as dimensionless length of water breakthrough, it's the ratio of the length of transition point of the front of oil-water and the length of formation. The computation of dimensionless length and gravity criterion of different permeability homogeneous formation models shows in Table 2. we can get a conclusion that there's obvious correlation between dimensionless length and gravity criterion (Figure 3), the bigger permeability of the core model, the smaller differential pressure gradient of displacement, the bigger gravity criterion and the greater gravity differentiation, thus, the shorter forward distance of transition point of the front of oil-water when water breakthrough of production side.

Table 2
Different Permeability Homogeneous Formation Model Results Contrast

Model number	Permeability /mD	Length /cm	Displacement pressure /KPa	Oil-water front turning point length /cm	Dimensionless length	Gravity criterion numeral
1	500	28	36.4	22	0.79	0.014
2	1,500	28	17.2	11	0.39	0.029
3	2,800	28	7.3	4	0.14	0.068

(b) Feature of oil-water distribution when displacement end time

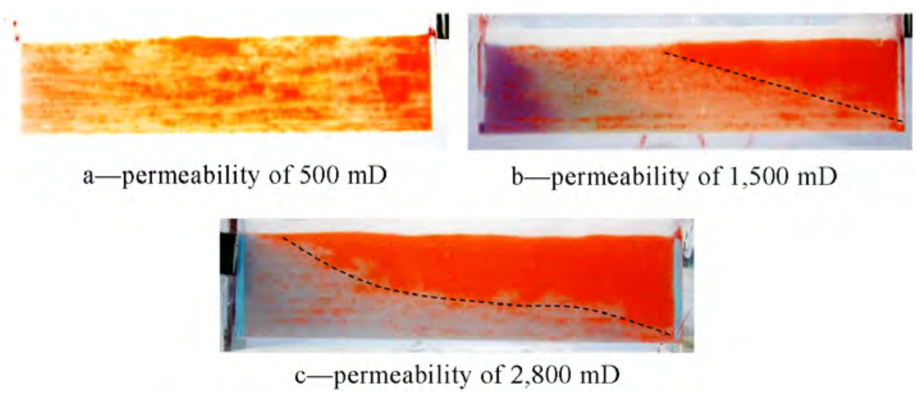


Figure 4
Different Permeability Homogeneous Formation Model Oil-Water Distribution on End Displacement Time

The contrasts of oil-water distribution on end displacement time for 3 different permeability homogeneous formations show that: The regular of water flooding is influenced by gravity and displacement force, the higher permeability, the bigger degree of water flooding influenced by gravity, the more obvious feature that water submerged at the model bottom, remaining oil concentrate at the model top. Water flooding homogeneity relatively for the low permeability model, the feature of remaining oil distribution of this model is scattered.

3.1.3 Dynamic Feature of Water Flooding

The relationship between different permeability homogeneous formation model water cut and recovery degree shows that (Figure 5): For the model which permeability is 500 mD, the recovery degree is 38.6% when water free production period end, and the recovery degree is 55.9% when limit water cut is 98% that of water submerged to production side. For the model which permeability is 1,500 mD, the recovery degree is 29.9% when water free production period end, and the recovery degree is 48.8% when limit water cut is 98% that of water submerged to the production side. For the model which permeability is 2,800 mD, the recovery degree is 21.7% when water free production period end, and the recovery degree is 42.1% when limit water cut is 98% that of water submerged to the production side. The results show that, the lower permeability of formation, the bigger water flooding swept volume, the later water breakthrough, the longer water free production period and the higher ultimate recovery degree. The higher permeability of formation, the faster water cut rise after water breakthrough, the contrasts of the condition of water cut rise to different permeability model show that, the degree of water flooding is relative low for higher permeability formation model.

3.2 Simple Rhythm Formation

3.2.1 Basic Parameters of Physical Model

The experiments include simple positive rhythm and simple reverse rhythm. The basic parameters of physical model: 28.0 cm long, 0.45 cm wide, 7.0 cm high. Furthermore, what the details of experiments show in Table 3.

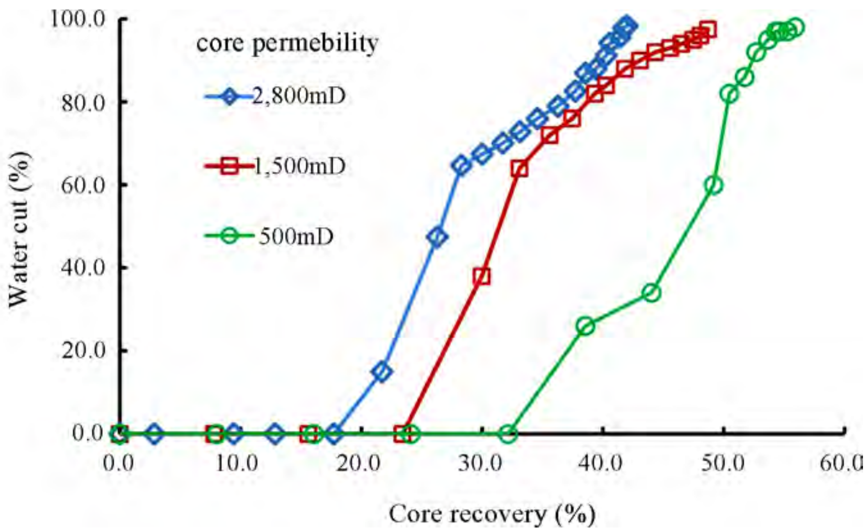


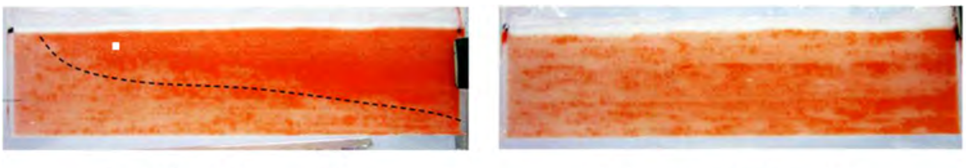
Figure 5
Different Permeability Homogeneous Formation Model Water Cut and Recovery

Table 3
Experiment Parameters of the Simple Rhythm Formation Model

Model	Total thickness /cm	Layer thickness /cm	Layer permeability /mD	Net weight /g	Wet weight /g	Porosity /%	Saturated oil /mL
		2.0	600				
positive rhythm	7.0	3.0	1,300	471.0	500.5	32.9	28.9
		2.0	1900				
		3.0	2,500				
reverse rhythm	7.0	2.0	1,500	458.5	487.1	31.6	27.9
		2.0	800				

3.2.2 Comparison of Experimental Results

(a) Distribution character of oil and water in the end of water displace process



a—positive rhythm model

b—reverse rhythm model

Figure 6
Simple Rhythm Formation Model Oil-Water Distribution in the End of Water Displace Process

The experimental results show that the different form between the positive rhythm model and reverse rhythm model. Cause of the gravity effect and permeability difference in the positive rhythm model, water displace the bottom high permeability layer, and remaining oil is distributed in the upper medium and low permeability layers in the end of water displace process. However, gravity effect plays a positive role in the reverse rhythm model, remaining oil is distributed relatively homogeneous, water can displace the upper medium and low permeability layers and the residual oil concentrated in the low permeability layer nearby the production well in the end of water displace process.

(b) Dynamic characteristics of water displace process

Figure 7 presented the relationship of water cut and recovery degree. In the positive rhythm model, the recovery percent of reserves 20.4% when water breakthrough (water displaced 0.22PV), and the ultimate recovery is 37.4% when water cut gets 98%. Yet, in the reverse rhythm model, the recovery percent of reserves 29.9% when water breakthrough (water displaced 0.43PV), and the ultimate recovery is 52.7% when water cut gets 98%. By the same way, a homogeneous rhythm model (1,500 mD) selected as a comparison, that recovery percent of reserves 29.9% when water breakthrough (water displaced 0.31PV), and the ultimate recovery is 48.8% when water cut gets 98%.

On account of the superposition effect of the gravity and permeability difference, water free oil production period in the positive rhythm model is shorter than the other two models, that reduced ultimate recovery. On the other hand, the gravity effect improves the vertical contradiction in the reverse rhythm model, water free oil production period is longer than the other two models, that increased ultimate recovery.

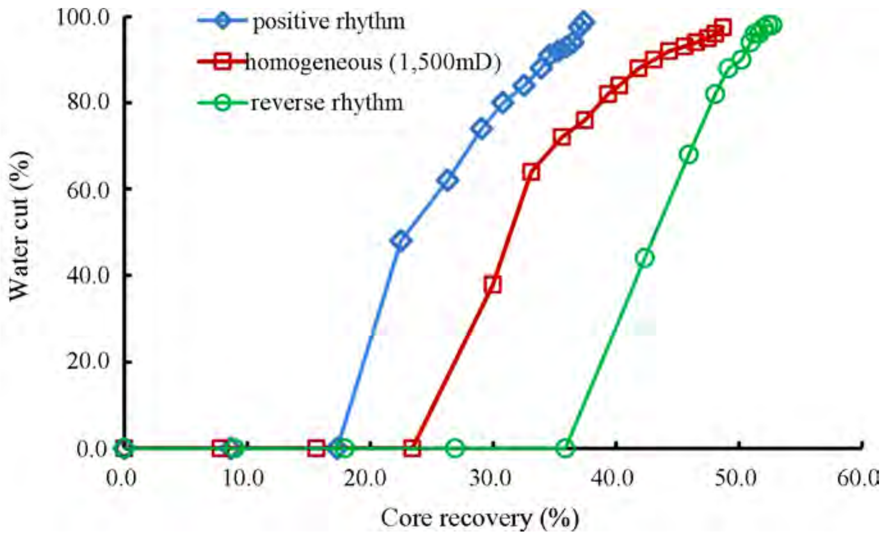


Figure 7
Simple Rhythm Formation Model Water Cut and Recovery Degree Contrast

3.3 Composite Rhythm Formation

3.3.1 Base Parameter of the Formation Model

In order to study the property of water flooding under different rhythm combination, according to the form of rhythm combination of well group, we design different rhythm combination models include composite positive rhythm, composite reverse rhythm, composite positive reverse rhythm and composite reverse positive rhythm, parameter of experiment shows in Table 4.

Table 4
Experiment Parameters of the Composite Rhythm Formation Mode

Model	Total thickness /cm	Layer thickness /cm	Layer permeability /mD	Net weight /g	Wet weight /g	Porosity /%	Saturated oil /mL
1	8.0	1.0	800	505.5	538.4·	37.8	33.2
		1.0	1,500				
		1.5	3,000				
		1.0	1,000				
		2.0	2,000				
		1.5	1,500				
2	6.0	1.0	2,100	484.7	509.1	30.1	22.8
		1.0	1,400				
		1.0	2,000				
		1.0	1,200				
		1.0	1,500				
		1.0	1,000				
3	8.5	1.5	1,000	518.7	556.9	36.9	39.5
		1.0	2,000				
		2.0	3,500				
		1.0	2,500				
		2.0	1,700				
		1.0	500				
4	8.5	1.5	3,500	518.1	552.7	32.9	35.2
		1.0	2,800				
		1.0	1,000				
		0.5	500				
		1.0	1,200				
		3.0	2,500				

3.3.2 The Comparison of Experimental Result

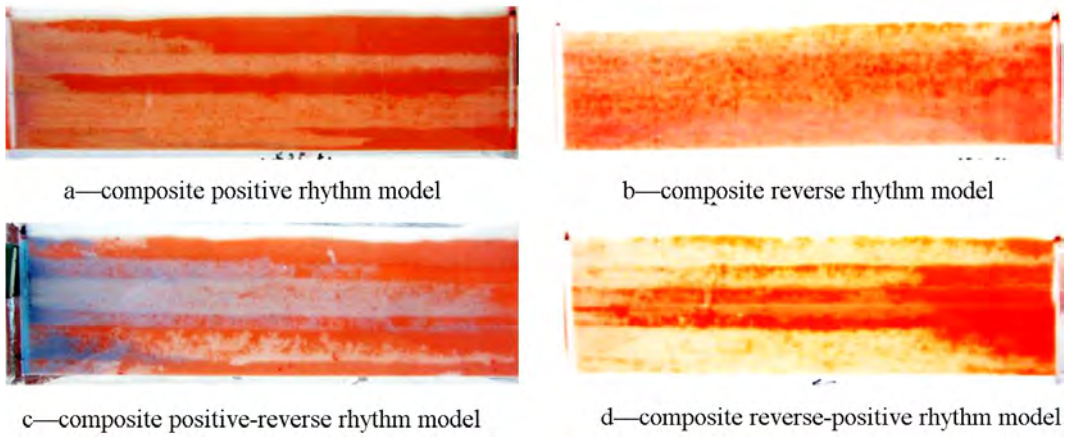


Figure 8
Composite Rhythm Formation Model Oil-Water Distribution on End Displacement Time

Composite positive rhythm formation model consist of multi-positive rhythm vertically, injection water breakthrough along high permeability layer, the water flood law and the character of residual oil distribution are similar to the single positive rhythm. Composite reverse rhythm formation model consists of multi-reverse rhythm vertically, the permeability range of the model is 2, therefore water drive is relatively uniform, there's not any sub layer breakthrough, and the effect of water drive for each layer is well. For the composite positive reverse rhythm formation model, injection water breakthrough along high permeability layer at the middle of the model, the water flood law and the character of residual oil distribution are similar to the single positive rhythm and single reverse rhythm model, residual oil distribution at the top and bottom low permeability layer of the model. For the composite reverse positive rhythm formation model, injection water breakthrough along high permeability layer at the top and bottom of the model, the water flood law and the character of residual oil distribution are similar to the single positive rhythm and single reverse rhythm model, residual oil distribution at the middle low permeability layer of the model.

CONCLUSION

The laboratory study of core flooding shows that the different rhythmic model of reservoirs shows different characteristics under the double influence of formation rhythm and gravity action. For homogeneous formations, the greater the reservoir permeability is, the more obvious the gravity effect is, and the remaining oil is concentrated in the upper part of the reservoir. For positive rhythm stratum model, gravity promotes longitudinal contradiction, injection water flow through the bottom of the high permeability layer, Anhydrous oil production period is short, the ultimate recovery is low, a large number of remaining oil enrichment in the low permeability reservoirs in the upper part of the reservoir. But the inverse rhythm stratum model slows that gravity slows down longitudinal contradiction, Water flooding is relatively uniform, Anhydrous oil production period is long, the ultimate recovery is high, No concentrated distribution for remaining oil after water flooding. The watered out law and residual oil distribution of the composite rhythmic stratigraphic model are the same as that of the single rhythm stratum. The experimental results can provide a guide for the oilfield adjustment direction. In the late stage of oilfield development, the potential of remaining oil mainly enrichment in local top of layer. The local potential measures can be considered to carry out at the top of the thick reservoirs by horizontal wells.

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