Driving Force Analysis of Sandstone Reservoirs with Strong Natural Aquifer

Zhanxiang Lei(✉), Jian Liu, Jian Li, Likun Xu, Lihong Fan, Yunbo Li, and Zhaopeng Yang

Research Institute of Petroleum Exploration and Development, Beijing 100083, China
{leizhanxiang, kevenlj}@petrochina.com.cn

Abstract. According to the 4 dimensionless parameters proposed by Djuro Novakovic, which are the ratio of length to height along displacement direction, the mobility ratio at endpoint, the gravity number and the capillary number, the quantitative limits can be obtained of viscous force, gravity and capillary force, respectively. With the typical models under different dominant driving forces, the development rules of water flooding were studied. Based on the actual formation attributes of the reservoir, the typical model was established, which was three dimensions (350 m × 350 m × 15 m) and three phases (oil, gas and water). And then, the influence of the dip angle, the aquifer and well pattern on the development effect was studied. It was indicated that, when the gravity was dominant, the degree of water flooding was relatively higher at the bottom of reservoir, but at the top, the sweep coefficient was smaller and in the plane the sweep efficiency was more uniform. While when the viscous force was dominant, the sweep efficiency in vertical direction was better than that in gravity case, but in the plane there appeared a more serious fingering phenomenon. Under the control of the capillary force, the sweep efficiency in vertical direction was the highest, and that in plane was also better than the viscous force case, which was basically consistent with the gravity case. Through the analysis of driving energy and driving mode, the rule of the water producing and its influencing factors of the target reservoir were clarified, and the influence of the loss of injected water on the reservoir development was summarized under the condition of the existence of the edge and bottom water. In the following

This paper was prepared for presentation at the 2018 International Field Exploration and Development Conference in Xi'an, China, 18–20 September, 2018.

J. Lin (ed.), *Proceedings of the International Field Exploration and Development Conference 2018*, Springer Series in Geomechanics and Geoengineering, https://doi.org/10.1007/978-981-13-7127-1_64

development and adjustment, in order to make the development scheme, we should take gravity as the dominant factor, consider the interaction between the injected water and the natural aquifer, and combine the optimized results of well pattern for injection-production.

Keywords: Dimensionless · Driving force · Gravity dominant · Development rules · Development scheme

1 Introduction

The strong natural water drive reservoir is a reservoir with large edge-bottom water. When the water body is large, the water influx to the reservoir will also increase. It provides more sufficient energy for the reservoir and slows down the degree of the pressure drop of the reservoir. Because of the large water energy, the water energy is lost in a short time of development, but the impact on its own can be ignored. When the physical property of the water area is good, the oil reservoir with large edge-bottom water can further strengthen the fluid exchange between water and reservoir, and then form a strong natural water drive reservoir, which is widely distributed in domestic and abroad at home and abroad [1–10].

A foreign reservoir is a strong natural water drive reservoir. After more than 30 years of development, it has entered the "double high" stage with high water cut and high recovery. Because of the strong edge-bottom water energy and the development strategy of side water injection, the production wells are water flooded seriously in the edge wells, and the two or three line production wells have low level of liquid production and even lack of fluid supply due to the lack of formation energy, which makes the production decline faster and the stable production is difficult. In this paper, through the analysis of driving energy and driving mode, the rule of the water producing and its influencing factors of the target reservoir were clarified, and the influence of the loss of injected water on the reservoir development was summarized under the condition of the existence of the edge and bottom water. In the following development and adjustment, in order to make the development scheme, we should take gravity as the dominant factor, consider the interaction between the injected water and the natural aquifer, and combine the optimized results of well pattern for injection-production.

2 Main Driving Force Identification

Djuro Novakovic [11] studies the limit of the index of different driving forces, and puts forward 4 dimensionless quantities, and the quantitative limits of the three driving forces of viscous force, gravity and capillary force are obtained respectively. The four dimensionless quantities are displacement height ratio, end point mobility ratio, gravity number and capillary force number. The definition are listed in Table 1. Different driving force dominant index limits are listed in Table 2 and Fig. 1.

Table 1. Dimensionless definition

Dimensionless	Symbol	Definition
Displacement direction and height ratio	N_{RX}	$\frac{L^2}{H^2}\frac{k_z}{k_x}$
Endpoint flow ratio	M	$\frac{\lambda^o_{rw}}{\lambda^o_{ro}}$
Gravity number	N_g	$\frac{k_z\lambda^o_{rw}A\Delta\rho g\cos\alpha}{v}$
Number of capillary force	N_c	$\frac{P_c\lambda^o_{rw}k_zA}{vH}$

Table 2. Dimensionless index limit of dominant modes with different driving forces

Dimensionless index	N_{RX}	$\frac{N_g}{M+1}$	$\frac{N_c}{M+1}$
Viscous force dominance	>100	<0.2	<0.2
Gravity dominance	>2	>5	$< 5\frac{N_g}{M+1}$
Capillary force dominance	>2	$< 5\frac{N_c}{M+1}$	>5

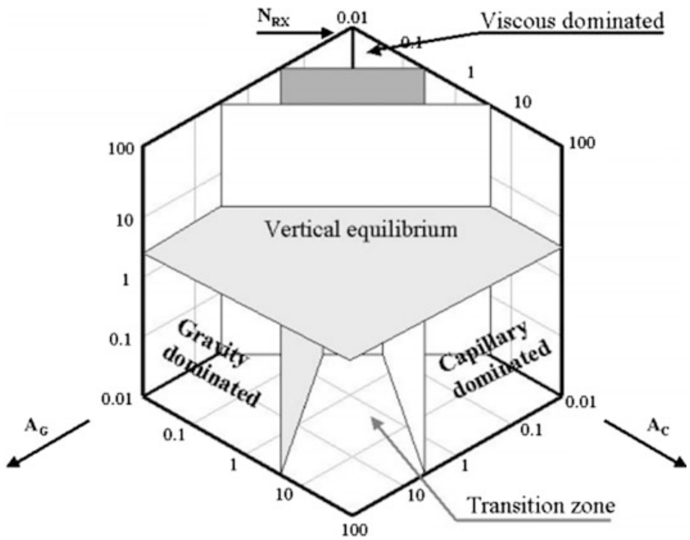


Fig. 1. Different driving force dominant index limits

3 Analysis of Different Driving Forces

According to the research conclusions of Djuro Novakovic, based on the basic physical parameters of the target reservoir, a typical model with different driving forces is established to meet the limit of the index defined by Table 1 and to study the water drive development law under the conditions of different driving forces.

3.1 Gravity Dominance

In the process of displacement, the conditions of gravity dominant are: the vertical permeability is larger, the thickness of the reservoir is larger, the density difference between the two phases is larger, the capillary force is smaller, the viscosity of the fluid is low, and the injection speed is low. In this case, the driving force is driven by a stable "gravity tongue", and the upward displacement effect is better than the downward displacement.

A typical model is designed to change the ratio of vertical permeability to plane permeability in the range of gravity dominant limits, and the influence rule of gravity on development effect is studied.

As can be seen from Figs. 2 and 3, the greater the ratio of vertical permeability to plane permeability, i.e., the stronger the gravitational force is, the faster the rising rate of water cut is, the lower the oil recovery.

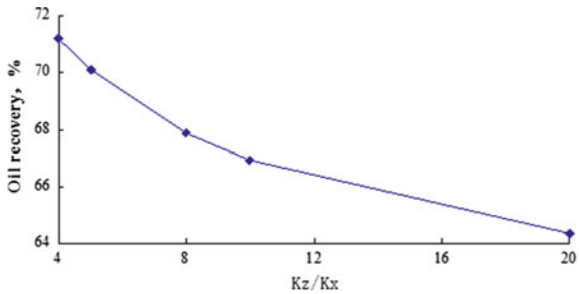


Fig. 2. Effect of gravity dominance on recovery

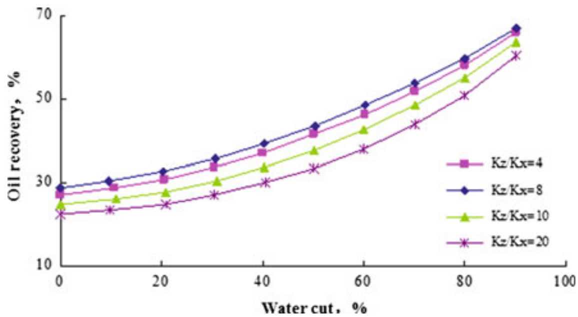


Fig. 3. Relationship between water cut and oil recovery under gravity dominated condition

3.2 Viscous Force Dominance

The forming conditions of the driving mode of viscous force dominance are as follows:

(1) high permeability reservoir with gentle dip angle and small vertical channeling.

(2) the interfacial tension between injected media and crude oil is very low, and even miscible.

Its characteristics are:

(1) it is similar to “piston type oil displacement”, and the oil-water interface promotes steadily
(2) in homogeneous reservoir, oil recovery is not affected by water injection rate.
(3) in the heterogeneous reservoir, the high permeability section has a fast flow rate and a low permeability section, and most of them are “small pore retention” remaining oil, see Fig. 4.

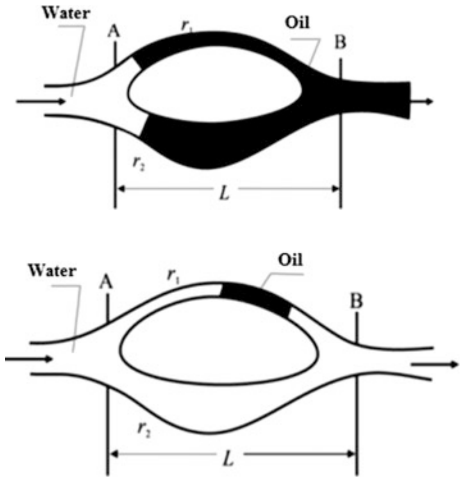


Fig. 4. Residual oil formed by “small pore retention” under viscous force dominance

In the range of viscous force dominant limits, the velocity of liquid production is changed, and the influence law of viscous force on development effect is studied.

From Fig. 5, it can be seen that the greater the liquid rate is, the stronger the viscosity strength is, the lower the ultimate oil recovery is. In the early stage of development, the higher the liquid rate is, the higher the oil recovery is at the same water cut, see Fig. 6. With the development of the water cut of 70%, the water cut of the high liquid rate increases and the final recovery rate becomes lower.

3.3 Capillary Force Dominance

The forming conditions of capillary force dominance include: (1) low permeability reservoir; (2) the wettability of the reservoir to displacement phase is good, even close to complete wetting, but this situation is rare.

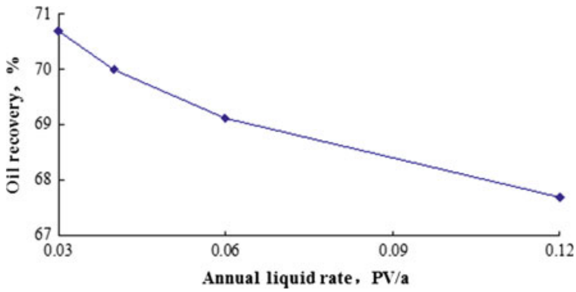


Fig. 5. Influence of viscous force dominance on oil recovery

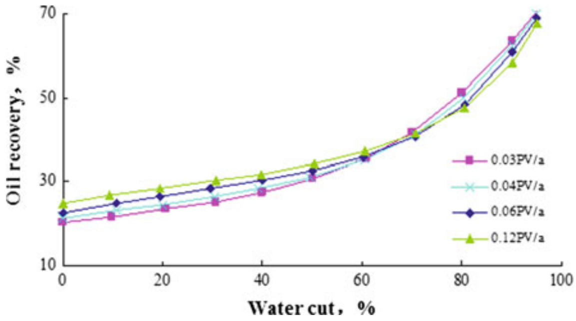


Fig. 6. Relationship between water cut and oil recovery degree of viscous force dominance

The displacement characteristics of the capillary force dominance are as follows:

(1) the flow velocity of fluid in the low permeability layer is greater than that in the high permeability layer, and even the phenomenon of "re-penetrate" low permeability layer in the high permeability layer.
(2) the formation of remaining oil is closely related to the wetting characteristics of reservoirs.
(3) the recovery rate is closely related to the injection intensity of displacement phase.

The capillary force is changed within the dominant limit, and the influence rule of development effect is studied.

As can be seen from Figs. 7 and 8, the greater the capillary force, the greater the longitudinal oil and water transition zone, the superior force of the capillary, the faster the rising of water cut and the lower the recovery.

3.4 Comparison of Different Driving Forces

The distribution of vertical oil saturation at the same time is obviously different from the models with different driving forces, such as Fig. 9. In the gravity dominant mode, the injected water is propelling to the production well with a stable "gravity tongue", which leads to the enrichment of the remaining oil at the top and the better bottom

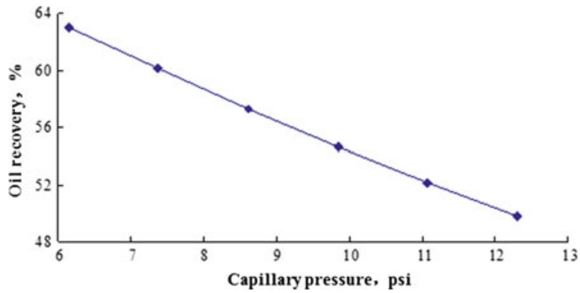


Fig. 7. Influence of capillary force dominance on oil recovery

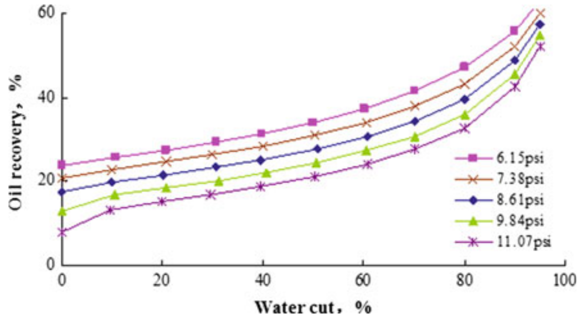


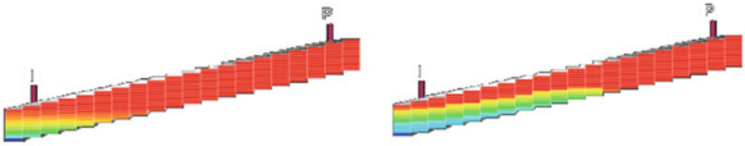
Fig. 8. Relationship between water cut and oil recovery of capillary force dominance

displacement. In the dominant mode of viscous force, the obvious viscosity "fingering" is caused by the high injection-production rate, and the rapid injection of water will lead to the earlier producing water in the production well. Under the condition of capillary force dominant, the vertical oil and water are too large, and the rate of water cut increases slowly.

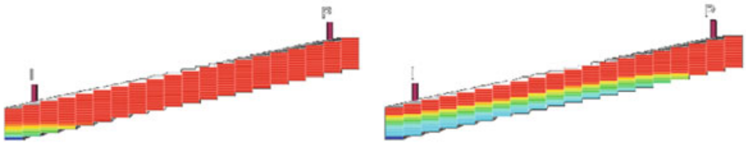
From the vertical distribution (Fig. 10) of the final oil saturation, it can be seen that in gravity dominance, the top remaining oil is most enriched, the vertical displacement effect is the worst, and it is better than viscous force dominance. The vertical displacement effect is best in capillary force dominance.

The distribution of final remaining oil in different driving forces is also different, shown in Fig. 11. When the viscous force is dominant, there are obvious fingering phenomena, the distribution of oil saturation in plane is the most uneven, the capillary force dominance is the second, and that in gravity dominance is the most unobvious.

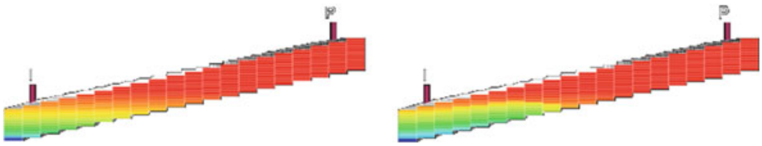
It can be seen that in gravity dominance, the water flooding of bottom in reservoir is high, but the top sweep coefficient is smaller and the plane sweep is more uniform. Under the viscous force dominance, the vertical sweep in reservoir is relative better than gravity dominance, but it will have a more serious fingering phenomenon in plane; in capillary force dominance, the vertical sweep coefficient in reservoir is the highest, and the sweep coefficient in plane is also better than the viscous force, which is basically consistent with gravity dominance. The block belongs to the dominant type of



(a) Gravity dominance

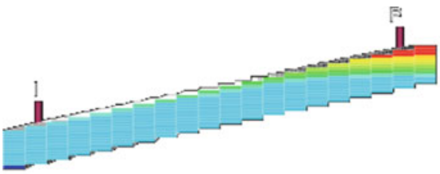


(b) Viscous domincance

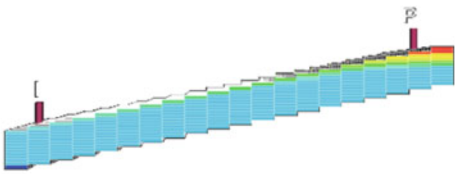


(c) Capillary pressure domincance

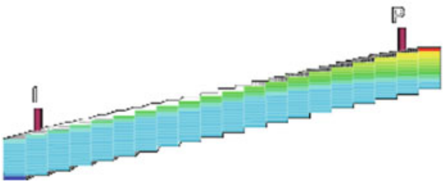
Fig. 9. Variation of oil saturation in different driving forces



(a) Gravity dominance

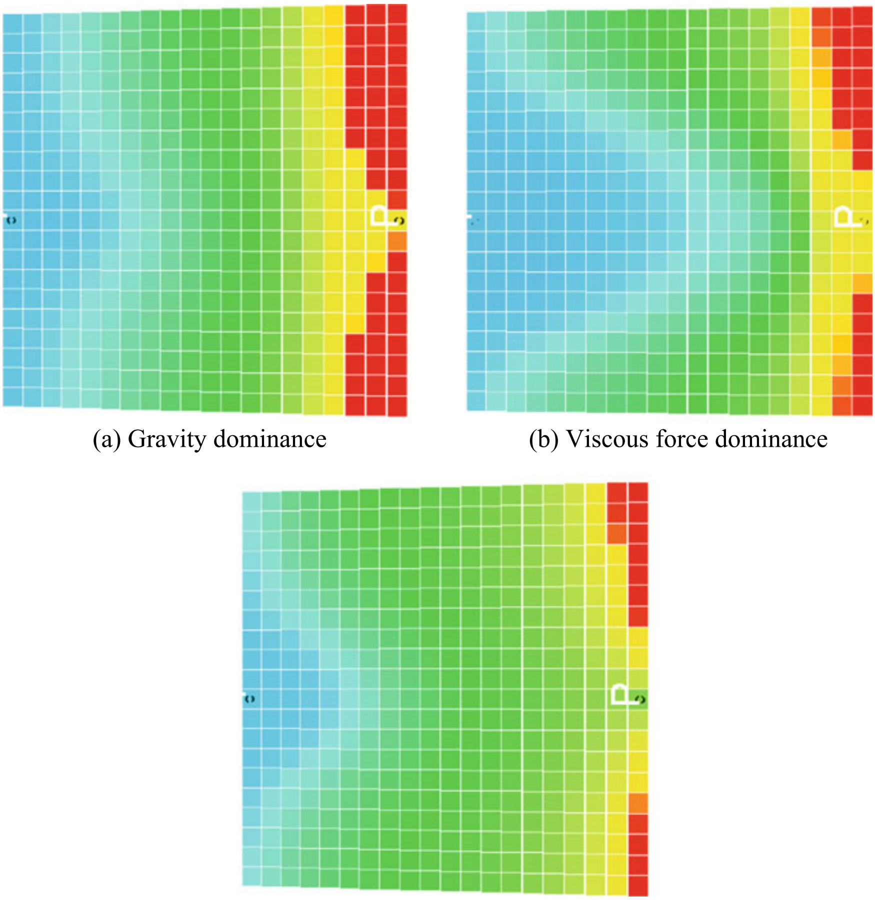


(b) Viscous force dominance



(c) Capillary dominance

Fig. 10. Distribution of final oil saturation in different driving forces dominance



(a) Gravity dominance (b) Viscous force dominance

(c) Capillary dominance

Fig. 11. The distribution of final remaining oil in different driving forces

gravity. Therefore, in the adjustment of late development, it is necessary to make use of the characteristic of gravity to make the bottom secondary water body even rise and advance, and then achieve the purpose of uniform wave. At this time, the horizontal well in the top side can be taken into consideration.

4 Conclusions

Based on the static and dynamic characteristics of the reservoir, the reservoir energy and main driving force types are evaluated by comprehensive application of reservoir engineering and numerical simulation, and the following aspects are summaried.

(1) Through the study of typical models, the development rules of gravity, viscous force and capillary force are obtained respectively, and the characteristics of the development of different driving forces and the distribution of residual oil are compared.
(2) According to the index boundaries of Djuro Novakovic, the main driving force of the target reservoir is gravity dominance.
(3) Through the analysis of the driving energy and driving mode, the rule of the water outlet of the target reservoir and its influencing factors are preliminarily clarified, and the effect of the loss of water flow on the development law of the reservoir is concluded under the condition of the existence of the edge-bottom water.
(4) In the process of subsequent development and adjustment, we should take gravity dominant as the dominant factor, and consider the interaction between the injected water and the water body, and combine the optimization results of injection and production well network to make the scheme of reservoir digging potential.

Acknowledgements. The authors would like to express appreciation for the financial support received from China National Key Project (2016ZX05031-001).

References

1. Ruiz SH, Wickramasekara S, Abrell L, Gao X, Chefetz B, Chorover J. Complexation of trace organic contaminants with fractionated dissolved organic matter: implications for mass spectrometric quantification. Chemosphere. 2013;91(3).
2. Amansky VB, Ho L, Maly PM, Seeker WR. Reburning promoted by nitrogen-and sodium-containing compounds. Symp (Int) Combust. 1996;26(2).
3. Zhao X, Lei Z, Chen H, et al. Production status and technical solutions for reservoirs with low relief structure and strong natural aquifer in Ecuador. PGRE. 2014;21(3):98–101.
4. Yu C, Wang Y. Application of injection profile date in layer optimized combination at late high water- cut stage of lower Es2 reservoir in Wen 51 block of Pucheng oilfield. PGRE. 2014;21(3):102–4.
5. Qi M, Zheng X, Wang G, Jia F, Li X, Yin Y. Study on rule of residual oil distribution of strong natural water-injection reservoir in 1AB depleted field of Peru. OGP. 2008;43 (Supplement 1):158–62.
6. Shen R, Li Z, Duan B, et al. Physical simulation of square inverted nine-spot pattern infilling and adjustment for low permeability reservoirs in western Wangyao oilfield. PGRE. 2014;21 (3):89–91.
7. Al Shalabi EW, Ghosh B, Haroun M, Pamukcu S. The application of direct current potential to enhancing waterflood recovery efficiency. Petrol Sci Technol. 2012;(20).
8. Dutton SP, Flanders WA, Barton MD. Reservoir characterization of a Permian deep-water sandstone, East Ford field, Delaware Basin, Texas. Am Assoc Petrol Geol Bull. 2003.
9. Stosur GJ, Singer MI, Luhning RW, Yurko WJ. Enhanced oil recovery in North America: status and prospects. Energy Source A. 1990;(4).
10. Blunt MJ. Flow in porous media—pore-network models and multiphase flow. Curr Opin Colloid Interface Sci. 2001;(3).
11. Novakovic D. Numerical reservoir characterization using dimensionless scale numbers with application in upscaling. Louisiana State University. 2002, p. 8.