Impact analysis of Reservoir Heterogeneity in the process of Water flooding

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Abstract

In multi-layer heterogeneity reservoir, the character of each layer differs greatly (such as porosity, permeability and fracture, etc). So does the water absorption capacity of each layer when water drive is adopted. Thus the adsorption profile of injection well, in great heterogeneity, which causes those layers of high porosity and fracture watered-out quickly, makes production well producing difficult, and makes the formation pressure decreasing rapidly due to the energy loss underearth. Therefore, how to thicken the accepting water layer and reduce the water-absorption-heterogeneity among each layer must be taken into account. Besides, under the action of injected water pressure, a part of oil can not be displaced due to viscosity resistance and capillary pressure. They are trapped in pores of rock thus the recovery is affected. Therefore, to conquer the negative effects that the heterogeneity of reservoir exerts on the improvement of oil recovery, it is quite important to discuss the profile control of injection well and water plugging of producing well, and research the mechanism of the remaining oil both existence and replacement. Injecting water to oil layer to make up the void due to exploit, thus complimenting the energy of layer and maintaining formation pressure to recovery, oil is called water flood recovery. Both confined by the geographic conditions and exploit level, the recovery efficiency is only about 40% on average, about 60% oil remained. This paper will study how to improve conformance efficiency and oil displacement efficiency so as to enhance the oil recovery.

Keywords

Heterogeneity, Porosity & Permeability, Water-flooding.

1. Introduction

Generally believed, the heterogeneity of layers is due to depositional conditions (such as depositional environment, migration speed of debris and marine regression or transgression). Secondary diagenesis and faulting exert effects too. Because of diversity of depositional conditions and quantity, types of rock, the lithology of oil layers differ from each other at both horizontal cross-section and vertical section, which divided into macro-heterogeneity and micro heterogeneity.

1.1 The effects of macro-heterogeneity of reservoir

Macro-heterogeneity means the heterogeneity of macro physical property parameters (porosity, permeability), the heterogeneity of permeability on vertical section makes the drive velocity different when water being injected, thus the thickness of watered-out layers is uneven. High permeable layer meets water too quickly, which decreases conformance efficiency. The heterogeneity of permeability on horizontal section results in uneven progressing of water line on horizontal section. Then some production wells will encounter water too early and be flooded, which affects the oil recovery, and oil displacement efficiency. Therefore, water plugging in producing well and adjusting water absorption profile for injection well is necessary. There are at least three main styles which cause macro-heterogeneity on real reservoirs.

Layering means the oil layers separated by those non-permeable layers and the changability of permeable on single oil layer profile and the heterogeneity of layer's characters along trend. These kinds of heterogeneity of oil bearing layer cause the uneven flow of fluid and affect recovery by reducing sweeping region of displacement agent. Generally, all those non-permeable layers make oil driving and production conditions worse, because they are obstructions to prevent oil flowing into well from all directions.

The differentiation of permeability, which means the characterized ability of layers that allow liquid or gas flow through, is the most important trait that control oil recovery efficiency. In vertical rock layers, permeability is the result of distribution of pores of different size. Such distribution results from the density of deposit, compaction, size grade and cementing etc. In carbonatite layers, the secondary dissolution and migration, recrystelliziment and dolomitisation also effect permeability. These factors change both with time and position during the course of oil-bearing layer formed. Because the change scale of permeability differs, the fluid flowing degree of freedom is confined. And those of course have something to do with the heterogeneity of fluid itself and the producing condition of well. Therefore, in heterogeneity layers with irregularly distributed permeability fluid can not move from bottom of layer to the top or from well to another well without confinement.

1.2 The effects of micro- heterogeneity

The permeability of real oil layer of rock relays on size grade, packing density and cementation type. The more the size grade of rock grain differs, the more the effective cross-section and surface trait varies, thus the micro- heterogeneity of pore space forms.

The pores in rocks can fall into capillary pores and sub-capillary pores. The radius of the former is bigger than 0.001 mm, and the latter's less than 0.001mm. Fluids show active only in capillary pores. And in sub-capillary pore fluids remain inactive due to the interacting molecular force between solids and liquids. If capillary pores have sub-capillary pore around, and without successive lanes, fluids can not move in capillary pores either.

The specific surface area of pore medium is one of the most important features for reservoir. For a reservoir with high permeability and porosity reservoir the specific surface area is no more than 500-1000 cm2/cm3, but as to silt-stone and low permeability carbonate, it may reach as high as 1000-3000 cm2/cm3. The trait is meaningful to improve oil recovery by physical-chemical method. Because any kind of chemical solution will interact with the surface of rock if remained in layers long enough for a time, a series of reaction will take place such as adsorption of chemical solution, damage of molecular exchangement between solution and rock, dissolution of salt etc.

One of the most important and basic characters of micro-constructure of oil layers' pore medium is surface wettability. What kind of wettability the pore medium has can determine the character of the course of water drilling oil, the distribution of remaining oil underground and the main measures taken to reduce remaining oil.

Almost all the oil and gas layers are formed in water medium (sediment deposit and cement). Besides, they have already contained water before reservoir comes into being. So they are water-wettable. In water-contained layer which under the function of gravity, reservoir can only be formed by the force of capillary pressure. With the effects of effective components (asphalt), oil drives water away from the surface of pores, and then this part of rock show lyophobic. We can drew the conclusion that the oil and gas layers have a mixed wettability (partly hydrohobic and partly lyophobic) or show a midterm state of wettability.

As above mentioned, the micro- heterogeneity of pore medium is a very important factor to decide to what extent can water or other solutions drive oil out.

2. The effect of oil viscosity

The viscosity of oil underground is a major parameter to determine the flowability or mobility of oil. The force or energy consumed by oil which flows from layer to well is in direct proportional to oil's viscosity, and the percolation velocity is in inverse proportional to it, if other conditions are the same.

The reservoir is difficulty to be recovered if its viscosity is larger than 50mP·s. Oil of different layers or reservoir from profile of a same oil field may be obviously distinguished. Viscosity of oil of a same reservoir may not be the same, either saying increasing from top to bottom or from one place to another. But generally no. In ordinary case, μO>μW.

$$M = \lambda_w / \lambda_0 = K_W \mu_0 / K_0 \mu_W \quad (1)$$

Where: KW--- effective permeability of water phase under remained oil's degree of saturation

KO--- effective permeability of oil phase under irreduable water's degree of saturation

μO,μW--- viscosity of oil and water

M--- mobility ratio

There, when M >1.0, oil is more mobile than water.

3. Way and mechanism of formation of remaining oil after water driving

Remaining oil includes two parts. Most of them are due to the failed driving of water, which indicate the whole layer is not exploited enough. This part of oil accounts for 60%-65%, the reason of which is serious macro- heterogeneity of the production layer. The other part is the oil in sweep area but had not been driven out. This part account for 35%-40%, which mainly result from micro- heterogeneity of watered-out layers, unstable percolation and some kinds of physical, physical-chemical factors.

The remaining oil due to the failure of totally sweeping of water is specific indications of macro-heterogeneity of reservoir. The antisotropism of permeability causes the front-line water and oil unevenly propelled. Once the flowing lane between injection well and production well is opened, almost all the water injected will flow into production well through this lane. The sweep area is difficult to be improved, and thus a great deal of oil is remained.

The formation of remaining oil in water swept area is mainly affected by the micro-heterogeneity of rock and wettability of rock surface and some other factors.

3.1 Separated capillary pore and single direction flowing liquid

From the permeability formula of capillary pore, we know that the flowing velocity V of single direction flowing fluid in capillary pore can be expressed as follow.

$$V = r2 \,\Delta P / 8 \,\mu l \quad (2)$$

The flow velocity V is mainly determined by the radius of pore and the viscosity μof the fluid. Under the pressure sink △P, percolation mainly happens in bigger pores. That is why there are more remaining oil in smaller pores.

3.2 Separated capillary pore, diphasic flow

If there are two kinds of liquids with viscosity μ1 and μ2 respectively in capillary pore whose radius is r, one of them can wet the surface of pore. The capillary force that shows the bend fluid level between the two phases is Pc. If the pressure exerted outside pore whose length is P1-P2, then the velocity of the boundary of the two phases is changeable. It relays on viscosity sink of two faces, radius r of the pore, time t of displacement, length Lc by which the boundary passes and pore's length L. That is as follows.

The movement of diphase flow in capillary is

$$v = \frac{r^2(p_1 - p_2 + p_c)}{8\sqrt{(\mu_2 L)^2 - (\mu_2 - \mu_1))[\ \frac{r^2 t}{4}(p_1 - p_2 + p_c) + 2\mu_1 L L_t - L_t^{\ 2}(\mu_2 - \mu_1)\ ]}} \tag{3}$$

Simulation of pore throat radius is

$$r = 0.5\sqrt{\frac{K}{\Phi}} \tag{4}$$

Where:K--- permeability of natural cores; Φ--- Porosity of natural cores

comparably complex when capillary force of bend boundary and viscosity sink exists. This is because ①The flowing velocities are different if the radius of pores are different. ②The flowing velocity is not fixed in the pores of same radius. It relies on viscosity sink, μO>μW. The flowing velocity keeps increasing when water drives oil. That is why fingering happens in capillary with different radius. Since the capillary force varies with the pore's radius, the uneven micro-fingering is more complex, which will affect recovery.

3.3 The example analysis

To Select 6 groups different permeability natural cores from some low permeable resevior. The number and physical property of these cores are shown in table 1. Using equation 3 to calculate the single capillary water flooding phase interface speed (Table 1).

Table 1. The boundary velocity of capillary with different radius

Sample number	Pore throat radius (μm)	Length (cm)	Viscosity difference(mPa.s)	Pressure difference(MPa)	Boundary velocity (cm/s)
X-11	1.5	4.5	4.40	2.93	0.00332
X-12	2.2	4.5	4.40	2.40	0.00586
X-13	3.1	4.5	4.40	2.35	0.0114
X-14	4.3	4.5	4.40	2.43	0.0226
X-15	5.4	4.5	4.40	2.45	0.0360
X-16	10.0	4.5	4.40	1.95	0.0984

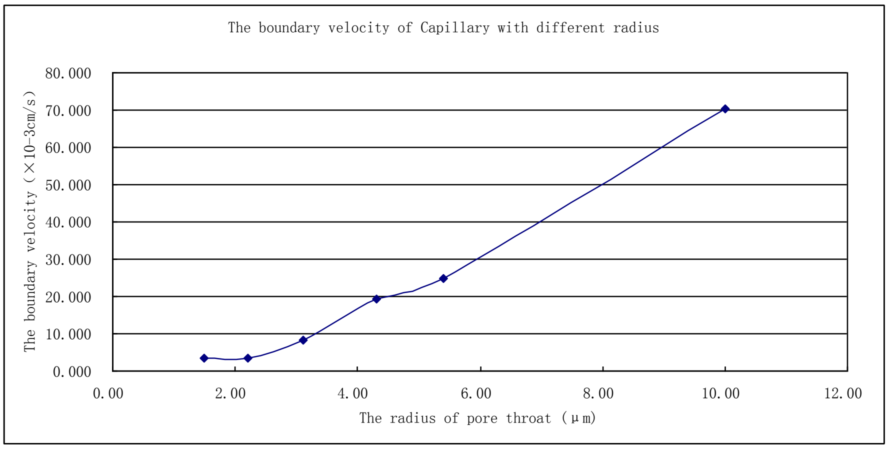

Figure 1. The boundary velocity of capillary with different radius

From table 1 and figure 1， it can be drawn that the oil-water interface velocity changes greatly with the pore throat radius increasing. Especially when the two capillary radius is nearly 7 times， then the flow rate may differ by nearly 30 times.

Oil water viscosity difference on the interface velocity impact is significant (Table 2).

Table 2. The boundary velocity of different viscosity difference

Sample number	Pore throat radius (μm)	Length (cm)	Viscosity difference(mPa.s)	Pressure difference(MPa)	Boundary velocity (cm/s)
X-11	1.5	4.5	4.40	2.93	0.00332
X-11	1.5	4.5	3.90	2.93	0.00174

From table 2， it can be drawn that interface velocity decreases nearly doubled with reduced viscosity difference 0.50mPa.s in the pressure difference between the ends of a certain.

To sum up， influence of capillary fingering velocity is the most important factor of pore throat radius and phase viscosity difference. So heterogeneous reservoirs in water flooding development should pay special attention to the water injection well plugging and appropriately increase the viscosity of water injection in order to minimize the reservoir heterogeneity and increase the injection water displacement efficiency.

3.4 The flow of mixed fluids in capillary pores

In a pore of same radius, if the radius of oil drop is close to that of the pore, the flow velocity decreases a lot. Since the surface of the pore has a absorption layer of abnormal viscosity, the plugging effect of scattered oil (or air bubble) remain oil easily which can not be ignored.

From above, we know that micro-percolation mechanism is the main reason that there remains oil after water driving. Consider the effects of wettiability remaining oil as follows.

If the solid phase is hydrophilic, behind the front of displacement, oil is drived from small pores to big ones under the capillary force by water to keep energy balance and minimize the free energy. There in micro-scale happens anti-percolation effect. That is to say, water occupies small pore (threat), while oil move to big pore and is trapped in water as scattered pearls. if partially water-lyophobic, oil exists as film on the surface of big pore where lyophobic oil film and oil pearls from small pores connected as one. In water-lyophobic reservoir, when water is injected, invisive and inredusible water mixed-up and stay in bigger pores, while the remaining oil discribute in smaller pores and cover the surface of pores as film.

4. Procedures and characters of remaining oil starting, scattering and migrating.

From the analysis above, we know the main way to produce remaining oil in non-water swept area is to enlarge water sweep area and improve the efficiency of water injection. while for the remained oil in water-outed area, we should start from its distribution trait to research the trait and regularity of starting, scatteration, migration and exploitage of remaining oil. The remaining oil mainly distribute in the following manner. Small pores of disadventaged percolation; big pores as oil pearls; pore's surface as film. These traits are due to micro- heterogeneity of reservoir, capillary force and surface wettiability. Follows are analysis of some classic cases.

4.1 Oil drops remained in big pores

To displace oil from changeable-section lane with water, capillary forces must be conquered.

$$Pc = 2\,\sigma\,(1/R2 - 1/R1) \quad (5)$$

where: Pc--- capillary force;σ--- interfacial tension;R1,R2 --- radius of oil drops

When water drives oil, the interfacial tension σ between two phases is as follows. Therefore, to make oil drops flow, σmust be reduced, and Pc tends to zero, smaller than hydrodynamic pressure sink ΔP/L. The shape of oil drops can be changed in any way, thus they can flow through pores and throats. Emulsified big oil peark and scatter them into small oil drops or oil thread to pass through throats. After that, they remain and stuff the pores on the rear as big oil pearls.

Besides, based on the Bernoulli's equation.

$$P2 - P1 = 2\sigma COS\theta \times (1/ R2- 1 / R1) > \Delta P / L \quad (6)$$

$$\sigma = 25 – 30 \ mN / m$$

When liquid flows from big section to smaller ones, V increases, and pressure sink decreases. The lose of △ P/L increases. Oil intends to stay at throats and then forms remaining oil.

4.2 Partial lyophobic surface, plenty of oil film remains on the solid surface after water driving

The existence of partial lyophobic surface cause rock engage oil directly, which means that the active surface of oil is absorbed by the surface of rock,and then the absorbed layer between oil and rocks forms. The size of the layer may as big as that of reservoir's pores.

4.3 Pores of H type

When the tension on the boundary of water and oil σ=25～30 mN/m and oil flows in both vertical pores and horizontal ones, remaining oil forms easily. Capillary force and viscous force must be conquered to drive it out. When alkali-surfactant-polymer flooding adopted, σdecreases to 10-3 mN/m. Since the effect of σ is negligible, only viscous force must be conquered to make oil move compared with water driving. The remaining oil is likely to be drived out for the lower resistance.

4.4 On the angle domain of pores

On the angle domain of pores, because of it's disadvantaged flow line, water flows mainly along the direction where pressure gradient is the greatest. The spin will happen when angle domain is encountered , the oil can not flow with the flow of water in main flowing lane. Instead, they keep spining at the former place and then remain at the original place.

5. Conclusion

In multi-layer heterogeneity reservoir, the character of each layer differs greatly. So does the water absorption capacity of each layer when water drive is adopted. The adsorption profile of injection well makes production well producing difficultly, and makes the formation pressure decreasing rapidly due to the energy loss underearth.

Under the action of injected water pressure, a part of oil can not be displaced due to viscosity resistance and capillary pressure. They are trapped in pores of rock and the recovery is affected.

It is quite important to discuss the profile control of injection well and water plugging of producing well, and research the mechanism of the remaining oil both existence and replacement to conquer the negative effects that the heterogeneity of reservoir exerts on the improvement of oil recovery.

By injecting water to oil layer to make up the void due to exploit, the conformance efficiency and oil displacement efficiency are raised a lot so as to enhance the oil recovery.

References

[1] Heiko Hillgartner,Wan Faisal Paino,Fahad Hadhrami, M., Integrated Reservoir Modeling for Water Flood Development in a Heterogeneously Fractured Carbonate Reservoir,North Oman, (2011),SPE-148380-MS.

[2] J.Toth, T.Bodi, and P.Szucs, M., Determining Effective Fluid Saturation, Relative Permeability, Heterogeneity and Displacement Efficiency in Drainage Zones of Oil Wells Producing Under Waterdrive, (2010),SPE-140783-PA.

[3] Z.J.Yin,G.Y.Lu,X.Zou, et al.Heterogeneity of non-marine reservoirs and its influences on recovery factor: take Gaoshangpu and Yonganzhen oil reservoirs in Jidong and shengli oilfields as examples.Oil & Gas Geology, Vol. 27(2006) No.1,p106-110,117.

[4] H.L.Xu.Effect of Plane Heterogeneity on Herringbone Well Steam Stimulation.Henan Science, (2015) No.2,p261-264.

[5] M.Sun.Heterogeneity Research of Chang 6 Reservoir in Luzigou Area,Erdos Basin.Journal of Chongqing University of Science and Technology:Natural Science Edition, Vol. 17 (2015) No.2,p25-28,47.

[6] Z.L.Fan,G.X.Zhang,G.Q.Wang, et al.Sedimentary microfacies and heterogeneity of Member 3 of Funing Formation of Biandong Oilfield.Science Technology and Engineering, Vol. 15 (2015) No.6,p164-169.