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RESEARCH PAPER

A theoretical discussion and case study on the oil-charging throat threshold for tight reservoirs

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Abstract: By analyzing the relationship between throat threshold and fluid forces of oil charge in tight reservoirs and according to the oil-charging mechanical conditions, the lower limits of throat at the interface between source and reservoir rocks and in the middle of reservoirs were determined theoretically. On the basis of Young-Laplace formula and the equilibrium between driving forces and capillary resistance, the threshold models were set up by using the maximum driving forces near the source-and-reservoir interface and inside reservoirs respectively. They were applied to the Yanchang Formation in the Ordos Basin, the middle-lower Jurassic in the Sichuan Basin and the Bakken Formation in the Williston Basin in America. The corresponding results near the interface are 15.74 nm, 29.06 nm, and 14.22 nm, and the ones in the middle of reservoirs are 39.45 nm, 37.20 nm, and 52.32 nm respectively. Accordingly, the threshold permeabilities of the three typical tight oil reservoirs calculated are 0.002 1×10^{-3} μm^2, 0.006 1×10^{-3} μm^2, 0.001 8×10^{-3} μm^2 near the interface and 0.010 0×10^{-3} μm^2, 0.009 4×10^{-3} μm^2, 0.016 9×10^{-3} μm^2 at the inner reservoirs. The rocks near the interface are complex, so there is a poor correlation between porosity and permeability, while inside reservoirs, homogeneous lithology results in good correlation between porosity and permeability. The porosity thresholds were determined as 2.16%, 2.00% and 3.50% respectively.

Key words: tight oil; oil-charging throat threshold; fluid forces; driving forces; theoretical discussion; case study

Introduction

The oil-charging throat threshold for tight reservoirs refers to the minimum diameter of throats through which oil can charge from the source rocks into reservoirs under geological conditions [1–2]. Studies on the threshold of throat in conventional reservoirs at home and abroad have mostly been based on statistical analysis of reservoir physical property data. Although this method is helpful in figuring out the throat threshold of oil-charging to a certain extent [2–5], it is hard to determine if it fully reflects the reservoir conditions or not, due to a lack of sufficient theoretical evidences. At present, for unconventional tight oil reservoirs, the threshold is generally worked out by summing up the thickness of bound water film and oil molecule diameter [1,6–8]. Although easy and simple, the method is limited in static conditions, and thus does not agree with the real geological conditions which are dynamic. The throat threshold of oil-charging is affected jointly by reservoir intrinsic characteristics, source rock characteristics, oil properties, and burial depth and history of reservoirs [9]. In this article, the process of oil charging into tight reservoirs is studied from the perspective of fluid forces; then relationship between the throat threshold of oil charging and mechanical action of fluid is analyzed; furthermore, the theoretical models of throat threshold of oil charging for tight reservoirs were established, according to the mechanical conditions for the charging process at the sourcerock-reservoir interface and inside the reservoir, as well as the Young-Laplace Equation [6,10]. Finally the throat thresholds of oil charging of Yanchang Formation in the Ordos Basin, Middle-Lower Jurassic Series of the Sichuan Basin and Bakken Formation of the Williston Basin in the US were worked out to provide references for reservoir evaluation.

1 Fluid mechanics factors affecting throat threshold of oil charging

Oil charging is mainly controlled by fluid mechanics. The driving force for oil charging near the interface between source rock and tight reservoir mainly comes from the pressure caused by hydrocarbon generation; the force inside the reservoir is the state pressure of tight oil under the corresponding conditions. Resistance preventing tight oil from

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getting into the reservoir is capillary pressure, and it increases with interfacial tension [10–11]. Formation-brokendown pressure affects the charging process by restricting the charging force, and in turn the throat threshold of oil charging [12]. Therefore, driving force, capillary resistance and formation-brokendown pressure are the main factors influencing the fluid mechanics of oil-charging in tight reservoirs, which will affect the throat threshold of oil charging directly [6–7].

1.1 Driving force of oil charging

1.1.1 Overpressure caused by oil generation near the interface between source rock and reservoir

Thin but tight, the interface between the source rock and the reservoir is the key part of oil charging. The characteristics of tight oil accumulation show that the process of tight oil expelling from source rocks and filling into the reservoir is driven by the overpressure caused by oil generation [13]. The higher the pressure increases caused by hydrocarbon generation, the more likely the tight oil fills the small throats near the interface where the source rock and the reservoir meet, and the lower the throat threshold of oil charging; and vice versa.

Based on the mechanism of hydrocarbon generation from kerogen and formation compaction, the theoretical calculation model of overpressure caused by oil generation is as follows [13]:

$$p_{\mathrm{g}}=\frac{FYM_{\mathrm{k}}\left[aD(1-p_{\mathrm{h}}C_{\mathrm{o}})-1\right]}{C_{\mathrm{w}}V_{\mathrm{w1}}\rho_{\mathrm{k}}+(1-YF)C_{\mathrm{k}}M_{\mathrm{k}}+aYFM_{\mathrm{k}}DC_{\mathrm{o}}} \tag{1}$$

(Y in the equation above is a parameter relating to HI, $Y=HI/1\ 000$)

1.1.2 State pressure of tight oil inside the reservoir

When tight oil overcomes the resistance at the source-reservoir interface and enters the reservoir, the throat space for migration becomes larger and as a result, the oil-charging force drops suddenly, and thus the force of driving oil into small throats decreases accordingly. Inside the reservoir, the state pressure driving tight oil fights against pore resistance. When the charging is balanced, the higher the state pressure of fluid, the lower the throat threshold allowing oil into the tight reservoir will be; and the lower the fluid state pressure, the higher the throat threshold will be. Therefore, the state pressure of tight oil inside the reservoir and the throat threshold of oil charging are negatively correlated.

Based on the van der Waals model of compressed fluid [14–15], the theoretical state equation for balanced tight-oil charging is established according to tight-oil components and the balancing pressure and temperature for charging. When tight oil charges from source rock to the nearby reservoir, the state pressure of fluid is balanced against the sum of capillary resistance and static water pressure. At a certain temperature, the state pressure and the volume of tight oil charging into the reservoir satisfy the modified van der Waals model [14]. Therefore, the state pressure of tight oil inside the reservoir is expressed as follows:

$$p_{\mathrm{s}}=p_{\mathrm{h}}+p_{\mathrm{c}}=\frac{RTV_{\mathrm{m}}}{{V_{\mathrm{m}}}^{2}-AV_{\mathrm{m}}+B}-\frac{\alpha}{{V_{\mathrm{m}}}^{\beta}} \tag{2}$$

Statistics show that the global tight oil is mainly light oil, with samiliar physical and chemical characteristics [6–7]. In order to determine the four parameters in the state equation (2), namely, A, B, α and β, tight oil samples were selected from Well Gong-26 in the Gongshanmiao Oilfield in central Sichuan, and their chemical components were analyzed using liquid chromatography, and results show that the main components C_{13}, C_{14} and C_{15}, are 4.13%, 4.03% and 3.89% in relative content respectively. Taking their relative contents as weight coefficients and according to the Van der Waals volume of C_{13}, C_{14} and C_{15} (139.87 mL/mol, 150.10 mL/mol and 160.33 mL/mol respectively) [15] and their acentric factors (0.623, 0.679 and 0.770 respectively) [16], the average Van der Waals volume of tight oil is worked out as 150.303 8 mL/mol and the average acentric factor as 0.692 1. According to the relationship between the coefficient A, B, α and β, and Van der Waals volume of tight oil and average acentric factors, the equations describing the charging state of tight oil are established with the determined coefficients:

$$A=3.034\ 6V_{\mathrm{w}}-5.43 \tag{3}$$

$$B=0.197\ 5A^{2.067\ 9} \tag{4}$$

$$\alpha=3.172\ 5A^{3.045\ 6} \tag{5}$$

$$\beta=1.539\omega+2.071 \tag{6}$$

$$p_{\mathrm{s}}=\frac{8.314TV_{\mathrm{m}}}{{V_{\mathrm{m}}}^{2}-450.68V_{\mathrm{m}}+60\ 744.24}-\frac{383\ 732\ 419.10}{{V_{\mathrm{m}}}^{3.14}} \tag{7}$$

1.2 Resistance of oil charging

The charging of tight oil is hindered by capillary pressure, viscous force and inertial force [6, 11]. Among them, viscous force and inertial force can be neglected due to low viscosity and low expulsion velocity of tight oil [17]. Therefore, only the capillary pressure needs to be considered as the resistance for oil charging at the source-reservoir interface and inside the reservoir. The higher the capillary pressure, the stronger the resistance and the higher the throat threshold of oil charging are. According to the Young-Laplace equation, the formula to calculate the capillary pressure is [10]:

$$p_{\mathrm{c}}=\frac{2\sigma\cos\theta}{r} \tag{8}$$

1.3 Formation-brokendown pressure restricting the maximum driving force of oil charging

If the overpressure caused by hydrocarbon generation at the source-reservoir interface and the tight oil state pressure inside the reservoir are both higher than formation-brokendown pressure, micro-fracturing will happen in the source rock and reservoir. As a result, the driving force will decrease near the formation-brokendown pressure [18]. With the generation and expulsion of tight oil, overpressure caused by oil generation