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STRESS SENSITIVITY OF HEAVY OIL RESERVOIR AND ITS INFLUENCE ON WELL PRODUCTIVITY

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Abstract—To investigate the characteristics of stress sensitivity of heavy oil reservoir and heavy oil, experimental study were carried out using core flooding system and on-line high-pressure caplastometer respectively. Results of experiments show that the core permeability of heavy oil reservoir show exponential decay along with the decrease of fluid pressure, while the viscosity of heavy oil show linear decrease. Based on the experiments, a new productivity equation of heavy oil reservoir with both permeability and viscosity sensitivity being taken into account was developed and field applied. The results reveal that well productivity with the consideration of permeability sensitivity is lower than that without the consideration of it; and well productivity with the consideration of viscosity sensitivity is higher than that without the consideration of it. In the case of both permeability and viscosity sensitivity being taken into account, the viscosity sensitivity can to some extent weaken the influences of permeability sensitivity on well productivity. Moreover, well productivity of heavy oil reservoir increases with the increment of viscosity sensibility coefficient. The newly-developed productivity equation can simulate the development characteristic of heavy oil reservoir more accurately and has certain advantages over the existing productivity equations.

Index Terms—heavy oil reservoir, permeability, viscosity, stress sensitivity, productivity equation

I. INTRODUCTION

During the development process of reservoir, the pore-fluid pressure will decrease along with the production of fluid, which will lead to an increasement of the effective stress exerted on reservoir rock [1]. As a result, the reservoir rock will be compacted and the permeability of reservoir rock will decrease, that is what called permeability sensitivity [2]-[4]. The existence of permeability will have an impact on the fluid flowability and oil/gas productivity.

Viscosity of crude oil is the reflection of the internal friction resistance of fluid itself in the flow of crude oil [5]. Viscosity characteristic of heavy oil has been studied at an ever increasing rate in the world. In former studies, viscosities of heavy oil were considered to be correlated with temperature only. Many papers have been published on calculating oil productivity in heavy oil reservoir, and most of the work to date has carried on calculation using constant viscosity in case of certain temperature[6]-[9]. However, for most heavy oil, especially the heavy oil under low temperatures, the viscosity is largely affected by pressure. In that case, if we ignore the viscosity sensitivity of heavy oil and calculate heavy oil productivity using constant viscosity values, it will lead to a big error in the final result.

To obtain a better understanding about development characteristic of heavy oil reservoir, and to analysis the influence of permeability and viscosity sensitivity on heavy oil development, experimental test were carried out to investigate the characteristics of stress sensitivity of heavy oil reservoir and heavy oil. Based on the experimental results, a new productivity equation of heavy oil reservoir with both permeability and viscosity sensitivity being taken into account was developed. The productivity equation proposed in this paper can lead to a more accurate simulation of development process of heavy oil reservoir

II. PERMEABILITY SENSITIVITY TEST OF HEAVY OIL RESERVOIR

A. *Experimental Method*

The force exerted on reservoir rock mainly include overburden pressure (external pressure) and pore-fluid pressure (internal pressure). The difference between two pressures is called effective stress [10]. Reservoir rock will be deformed due to the change of effective stress, and the permeability of reservoir rock will change as well, that is what called permeability sensitivity. Therefore, we can investigate the permeability sensitivity of reservoir rock in the laboratory by simulating the change of effective stress. According to the definition of effective stress, there are two ways to simulate the changement: changing pore-fluid pressure meanwhile fixing overburden pressure and changing overburden pressure meanwhile fixing pore-fluid pressure.

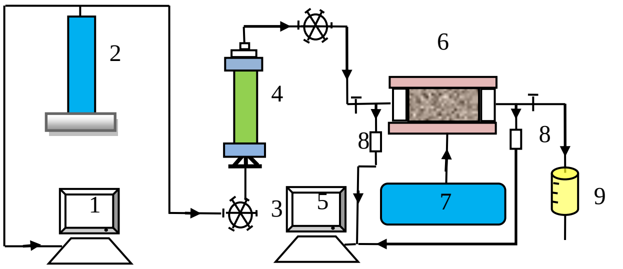
To make experiments easier to run, most scholars used to carry out the permeability sensitivity test under fixed pore-fluid pressure and variable overburden pressure [11]-[14]. However, this kind of experimental method do not match the development process: During the development process of oil reservoir, the overburden pressure do not change, however, the pore-fluid pressure will decrease due to the production of oil/water. Therefore, the experimental method of changing pore-fluid pressure meanwhile fixing overburden pressure can match the actual development process better. In this study, sensitivity test was carried out under fixed overburden pressure and variable pore-fluid pressure to analysis the character of permeability stress sensitivity of heavy oil reservoir.

B. *Materials & Conditions*

1) Cores used in this experiment are natural cores form a heavy oil reservoir in northeastern China, which have an average porosity of 20.37% and an average permeability of $299\times10^{-3}\mu m^2$.
2) Fluid used in this experiment is high purity nitrogen with a purity of more than 99.999%.
3) Experimental temperature is 82˚C (original formation temperature).
4) To make experiments match the actual condition of reservoir better, experiments were carried out using cores with irreducible water.

C. Experimental Procedure

A schematic drawing of the experimental procedure is shown in Fig.1.



1. Pressure & Flow Control System; 2. RUSKA Pump;
3. 6-Way Valve; 4. High Pressure Vessel;
5. Pressure Acquisition System; 6. Core Holder;
7. Confining Pressure Pump; 8. Pressure Sensor; 9. Flow meter

Fig.1. Schematic of permeability sensitivity test.

D. Results and Disscussion

Permeability sensitivity behaviors of the two tested cores are shown in Fig.2.

As can be seen from Fig.2, the core permeability of heavy oil reservoir show exponential decay along with the decrease of pore-fluid pressure. In the early stage of the experiment, the core permeability decrease quickly and then become slowly in the later stage. Comparing the two curves in Fig.2, we can see that the changing amplitude of curve of permeability sensitivity reduces as the decrease of original permeability, which indicates that the permeability sensitivity gets weaker along with the decrease of original permeability.

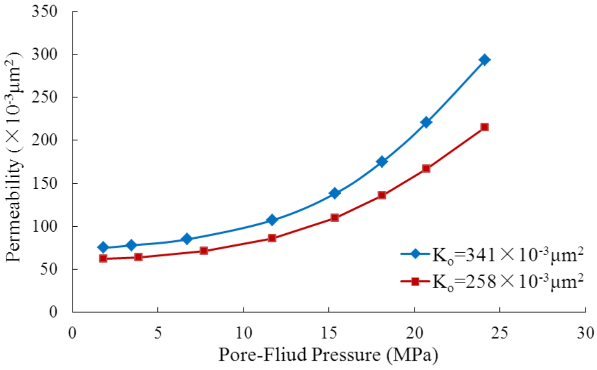


Fig.2. Permeability sensitivity behaviors of different cores.

Results of the experiments show that, the core permeability of heavy oil reservoir change dramatically with the pore-fluid pressure (heavy oil reservoir has strong permeability sensitivity). Therefore, during the development process, core permeability are not constant value, the permeability sensitivity cannot be ignored in engineering calculation.

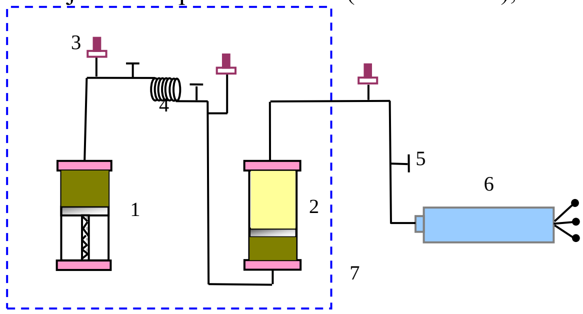
III. VISCOSITY SENSITIVITY TEST OF HEAVY OIL

A. Materials & Conditions

1) Oil used in this experiment is degassed crude oil form a heavy oil reservoir in northeastern China.
2) To obtain the character of viscosity sensitivity of heavy oil, viscosity of heavy oil is measured under different pressures. Experimental temperature is from 55˚C to 85˚C (original formation temperature).

B. Expermental Procedure

Viscosity sensitivity test was carried out using on-line high-pressure caplastometer in RUSKA PVT-2730. The schematic drawing of the experimental procedure is shown in Fig.3.



1. Pump Cell; 2. Float Piston Cell; 3. Pressure-Difference Sensor; 4. Capillary; 5. Valve; 6. Pump; 7. Calorstat

Fig.3. Schematic of RUSKA online high-pressure caplastometer.

C. Results and Disscussion

Viscosity of heavy oil under different pressures and temperatures are shown in Fig.4.

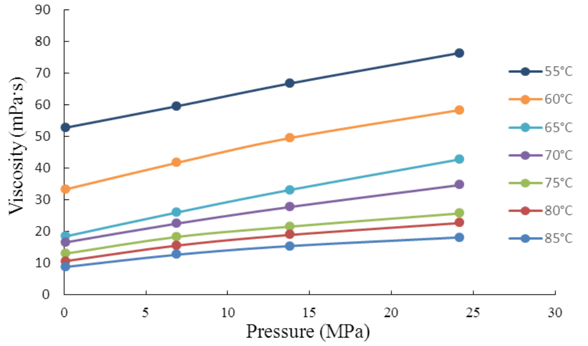


Fig.4. Viscosity sensitivity behaviors of heavy oil.

As can be seen from Fig.4, the viscosity of heavy oil show linear increase with the increase of fluid pressure. And at lower temperature, the original viscosity of heavy is higher, and the increasing rate is higher as well.

To obtain the quantitative characterization of viscosity of heavy oil under different pressures, linearity fit of experimental data were performed, results are shown in Table. I.

Table I. Heavy oil viscosity equations under different pressures &temperatures

Temperature /°C	Viscosity Equation	Correlation Coefficient
55	$\mu=52.907+0.9843P$	0.9994
60	$\mu=34.129+1.0395P$	0.9918
65	$\mu=18.838+1.0088P$	0.9982
70	$\mu=17.033+0.7486P$	0.996
75	$\mu=13.917+0.5159P$	0.9738
80	$\mu=11.505+0.4907P$	0.9729
85	$\mu=9.5268+0.382P$	0.9667

Table. I shows that at a certain temperature, the viscosity of heavy oil can be represented as a linear function change with pressure, and the correlation coefficient is high enough. That means the viscosity of heavy oil can be represented as equation (1):

$$\mu = \mu_0 + c \cdot p \qquad (1)$$

Where: μ—viscosity of heavy oil under different pressures, mPa.s; μ_0— viscosity of heavy oil under atmospheric pressure, mPa.s; c— viscosity sensibility coefficient of heavy oil, dimensionless; p— present pressure, MPa.

Fig.3 and Tbl.1 show that the viscosity of heavy oil are not constant values, they are going to increase along with the increase of pressure, and the increasing rate is higher under low temperature. Therefore, if the viscosity are set as constant values in the engineering calculation of heavy oil reservoir, it will lead to a big error in the final result. To achieve a higher accuracy, viscosity sensitivity should be taken into account in the engineering calculation.

IV. PRODUCTIVITY EQUATION OF HEAVY OIL RESERVOIR WITH STRESS SENSITIVITY BEING TAKEN INTO ACCOUNT

According to the equation for steady radial flow towards an oil well [15]:

$$\frac{dp}{dr} = \frac{\upsilon\mu}{K} \tag{2}$$

$$\upsilon = \frac{q}{2\pi rh} \tag{3}$$

$$q = \frac{2\pi rhK}{\mu} \cdot \frac{dp}{dr} \tag{4}$$

According to the theory of primary effective stress [1], the change of core permeability with pore-fluid pressure can be presented as follows:

$$K = K_i \cdot e^{-b\phi(p_i - p)} \tag{5}$$

Where: K— present permeability of reservoir, $10^{-3}\mu m^2$; K_i— original permeability of reservoir, $10^{-3}\mu m^2$; b—permeability sensibility coefficient of reservoir, dimensionless; p_i— original formation pressure, MPa.

As presented in section III, viscosity sensitivity of heavy oil can be represented as equation (1).

Substituting equation (1) and (5) into equation (4), we can obtain the filtration equation of heavy oil reservoir with both permeability and viscosity sensitivity being taken into account, shown in equation (6).

$$q = \frac{2\pi rh}{\mu_0 + c \cdot p} K_i \cdot e^{-b\phi(p_i - p)} \cdot \frac{dp}{dr} \tag{6}$$

Equation (6) is solved numerically by the path integral method, result is shown as follows:

$$\int_{r_w}^{r_e} \frac{q}{2\pi rh} dr = \int_{p_{wf}}^{p_e} \frac{K_i \cdot e^{-b\phi(p_i - p)}}{\mu_0 + c \cdot p} dp \tag{7}$$

Let

$$y = \frac{\mu_0 b\phi}{c} + b\phi \cdot p \tag{8}$$

Substituting equation (8) into equation (7) and equation (7) can change into:

$$\frac{q}{2\pi h} \ln \frac{r_e}{r_w} = \frac{K_i}{c \cdot e^{\frac{\mu_0 b\phi}{c} + b\phi p_i}} \int_{\frac{\mu_0 b\phi}{c} + b\phi p_{wf}}^{\frac{\mu_0 b\phi}{c} + b\phi p_e} \frac{e^y}{y} dy \tag{9}$$

Expanding the right side of equation (9) into Taylor series, it will be accurate enough by retaining the preceding two items, then equation (9) can change into equations as follows:

$$\frac{q}{2\pi h} \ln \frac{r_e}{r_w} = \frac{K_i}{c \cdot e^{\frac{\mu_0 b\phi}{c} + b\phi p_i}} [\ln \frac{\frac{\mu_0 b\phi}{c} + b\phi \cdot p_e}{\frac{\mu_0 b\phi}{c} + b\phi \cdot p_{wf}} + b\phi(p_e - p_{wf})] \tag{10}$$

$$q = \frac{2\pi K_i h}{c \cdot e^{\frac{\mu_0 b\phi}{c} + b\phi p_i} \cdot \ln \frac{r_e}{r_w}} [\ln \frac{\frac{\mu_0 b\phi}{c} + b\phi \cdot p_e}{\frac{\mu_0 b\phi}{c} + b\phi \cdot p_{wf}} + b\phi(p_e - p_{wf})] \tag{11}$$

Equation (11) is the productivity equation of heavy oil reservoir with both permeability and viscosity sensitivity being taken into account

V. CASE STUDY

A heavy oil reservoir X located in northeastern China, reservoir X has an average porosity of 23.2%, the original permeability of reservoir is $461\times10^{-3}\mu m^2$, the thickness of reservoir is 8.9m, original formation pressure is 9.2MPa, the drainage radius is 90m and the effective well radius is 0.12m. The boundary pressure and bottom hole pressure are 9.2MPa and 1.13MPa respectively.

Take heavy oil reservoir X as example, productivity curve were calculated by using the productivity equation developed in section IV to analysis the influence of stress sensitivity on productivity of heavy oil reservoir. Results are shown in Fig.5.

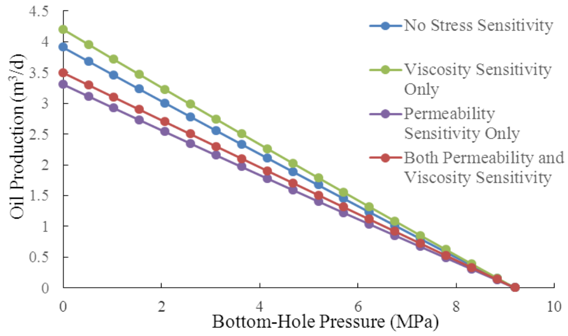


Fig.5. Oil production curves under different stress sensitivity conditions

As can be seen from Fig.5 that well productivity with the consideration of permeability sensitivity is lower than that without the consideration of it, which is because along with the development process, the pore-fluid pressure 1decrease, and permeability 1decrease as well because of permeability sensitivity, as a result, the crude oil is more difficult to flow and the productivity will decrease. Well productivity with the consideration of viscosity sensitivity is higher than that without the consideration of it. That is because along with the decrease of pore-fluid pressure, the viscosity of heavy oil decrease and it is easier to flow in the reservoir for heavy oil, that's why the productivity goes up.

In the case of both permeability and viscosity sensitivity being taken into account, the productivity is lower than without the consideration of stress sensitivity, but higher than with the consideration of permeability sensitivity only. That indicates that the viscosity sensitivity can to some extent weaken the influences of permeability sensitivity on well productivity. Therefore, in the engineering calculation, permeability sensitivity and viscosity sensitivity both cannot be ignored.

The productivity contrasts under different viscosity sensitivity coefficients are shown in Fig.6.

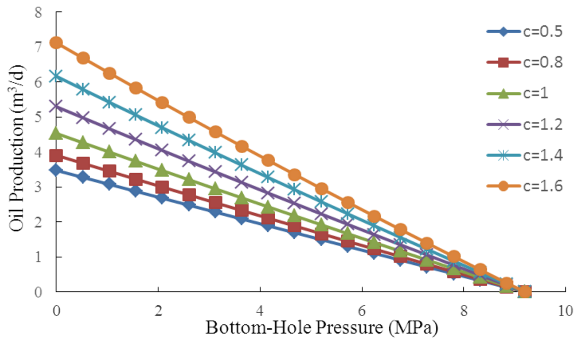


Fig.6. Productivity contrasts under different viscosity sensitivity coefficients

It can be seen from Fig.6 that well productivity of heavy oil reservoir and ultimate oil production increases with the increment of viscosity sensibility coefficient. The increasing rate of productivity and ultimate oil production goes higher as the increment of viscosity sensibility coefficient as well.

VI. CONCLUSIONS

1) Core permeability of heavy oil reservoir change obviously with the pore-fluid pressure: core permeability of show exponential decay along with the decrease of pore-fluid pressure. And permeability sensitivity gets weaker along with the decrease of original permeability
2) At a certain temperature, the viscosity of heavy oil are not constant values, they show linear increase along with the increase of pressure, and the increasing rate is higher when the temperature is low.
3) Based on the experiments, a new productivity equation of heavy oil reservoir with both permeability and viscosity sensitivity being taken into account was developed and field applied. The results reveal that well productivity with the consideration of permeability sensitivity is lower than that without the consideration of it; and well productivity with the consideration of viscosity sensitivity is higher than that without the consideration of it. In the case of both permeability and viscosity sensitivity being taken into account, the productivity is lower than without the consideration of stress sensitivity, but higher than with the consideration of permeability sensitivity only. For heavy oil reservoir, the viscosity sensitivity can to some extent weaken the influences of permeability sensitivity on well productivity.
4) Well productivity of heavy oil reservoir and ultimate oil production increases with the increment of viscosity sensibility coefficient. The increasing rate of productivity and ultimate oil production goes higher as the increment of viscosity sensibility coefficient as well.

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