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Research Article

Inflow Performance of Foam Oil Well Based upon Micro-bubble

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Abstract: Such thesis, from the micro perspective, obtains bubble quantity and their distribution in oil phase under different pressures by means of establishing formation and growth model of the bubble in foam oil so as to form property model of foam oil and then constitute inflow performance model of foam oil occurring in cold production for heavy oil reservoirs via modifying inflow performance relationship for conventional crude oil so as to use for output forecast of foam oil production well in cold production for heavy oil. The research indicates that the formation and growth of bubbles occurring in cold production for heavy oil reservoirs have critical influence on the property of foam oil and also affect its development trend; the model calculation reveals that IPR curve of foam oil in cold production for heavy oil reservoirs , significantly different from that calculated upon conventional model, is in adverse trend and in line with the development characteristics of foam oil; the IPR curve upon theoretical model is consistent with that upon CMG-STARS model in tendency, but there is still some difference for the bubble broken is not considered in theoretical model. Consequently, the curve upon theoretical model has obvious down jog and the error occurs to some extent so that the model shall be modified further.

Keywords: Bubble growth, bubble quantity, foam oil, IPR curve, micro-bubble

INTRODUCTION

The inflow performance of oil well refers to the relationship between the fluid (oil, gas, water) production and the corresponding flowing bottom hole pressure under the certain pressure of hydrocarbon reservoir and reflects the capacity for supplying oil and gas to the well of the oil reservoir (Chen and Hu, 2000). The common method for calculating the relationship between the current and future flow performances comprises Vogel method, Wiggins method, Standing method, Fetkoich method (Wang *et al*., 1999).

During the dissolved gas drive processes of the heavy oil reservoirs in Canada and Venezuela, a relatively high yield and a primary recovery ratio are shown, the wellhead crude oil samples collected from these oil fields present a foam status of continuous oil phases and contain a large number of bubbles and these bubbles are very stable. The production data of these oil fields indicates that the production characteristics and conventional dissolved gas-drive reservoirs are quite different (Maini and Ma, 1986). The single well shows an exceptionally high yield and the actual production of crude oil is higher than 10 to 30 times of theoretically expected production (Poon and Kisman, 1992). Moreover, people connects the good development performance of heavy oil cold production with the foam characteristics of ground heavy oil and calls this as a foam oil mechanism, wherein an important reason which is generally considered of the phenomenon is that the large number of micro-bubbles which are difficult to break and formed in the heavy oil are formed into foam oil together with the crude oil (Brij *et al*., 1997). According to the theory of nucleation, the smaller bubbles are formed by means of a high supersaturation (Sun *et al*., 2004), a relatively stable foam oil phase is presented and therefore the yield is high, the gas-oil ratio of production is low and the recovery ratio of heavy oil reservoir is significantly improved finally, as shown in Fig. 1.

In conventional oil reservoirs, the gas phase will overflow from the oil phase when the pressure is reduced to the degree of less than the pressure of bubble point, the number and volume of the bubbles will be rapidly increased with the reduction of pressure and a continuous gas phase will be formed by means of bubble fusion and rupture; for the conventional oil reservoirs, the time of bubble formation and rupture is very short, so that the process is ignored frequently. However, in the foam oil, the bubbles generated in the oil phase will not fuse or rupture while existing in the oil phase in the form of dispersed and minute bubbles. With the reduction of pressure, the number and volume of the bubbles in the oil phase will be increased and the bubbles will be fused and ruptured to form a free phase only under the condition that the pressure is reduced to

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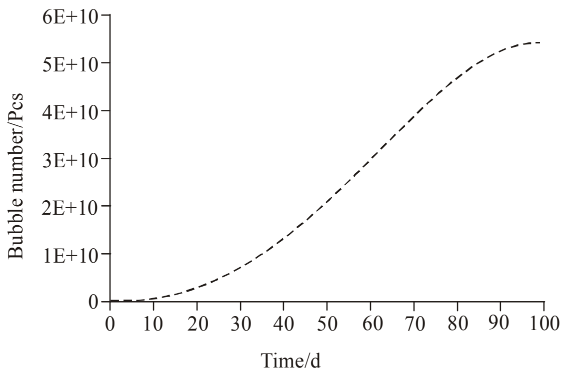

Fig. 1: Curve of bubble number in oil phase

the degree which is considerably lower than the pressure of the bubble point.

Due to the difference between the flow characteristics of heavy oil reservoir and conventional oil reservoir, the inflow performance of the oil has not been studied well during the cold production process of heavy oil reservoir. In the study, the formation and growth models for the bubbles in the foam oil are created, from the microscopic point of view, to get the number and size distribution for the bubbles in the oil phase of different pressures, thereby establishing the nature model of foam oil and establishing the inflow performance model of the foam oil during the heavy oil reservoir and cold production process by correcting the relational expression for the inflow performance of conventional crude oil, wherein the inflow performance model is applied to the production capacity forecast for the foam oil production well presented in the cold production process of heavy oil.

MATERIALS AND METHODS

Bubble model of foam oil:

Bubble nucleation:

$$J = 2N\left(\frac{2\sigma}{\pi m B}\right)^{1/2} \exp\left(-\frac{16\pi\sigma^3}{3kT\Delta P^2}\right) \tag{1}$$

In the formula, J represents the bubble nucleation frequency of oil phase.

In fact, when the oil phase is constant, the surface tension, temperature and other factors of the oil phase are constant values. Therefore, the unique variable which will impact the number of bubble nucleation in the oil phase is the supersaturation therein. According to the relational expression and experiments, it can be indicated that the supersaturation in the oil phase is proportional to the number of the bubbles formed in the supersaturation. During the process of pressure depletion, the supersaturation in the oil phase is changed by following the change of pressure. Thus, the number of bubble nucleation in the oil phase is also changed with the pressure depletion.

Some authors obtained the relational expression of bubble nucleation in the oil phase by means of experiments, in which the relational expression of bubble nucleation in the porous medium oil phase obtained by wood is as follows (Moulu, 1989):

$$J = 9\times 10^{-3}\exp\left(-\frac{16.5}{\Delta P^2}\right) \tag{2}$$

In the formula, ΔP represents the super saturation in the oil phase.

The relationship between the supersaturation in the oil phase and the number of bubble nucleation is accurately described in some overseas experiments.

Bubble growth: The growth stage of the bubble is subsequent to the bubble nucleation and the mechanisms and main influential factors of the two stages are different (Zhao *et al*., 2011). In the bubble nucleation stage, the energy is mainly consumed in the formation of the gas phase; in the bubble growth stage, the gas phase has been formed, the power of growth is obtained from internal bubble pressure and the resistance is generated by the viscosity and external pressure of the oil phase (Patel, 1980). The equation for describing the growth of bubble mainly comprises a hydrodynamic equation and a diffusion equation.
The hydrodynamic equation is as follows:

$$P_g - P_i = \frac{2\sigma}{R} + \rho_l\left[\frac{3}{2}\dot{R}^2 + R\ddot{R}\right] + 4u\frac{\dot{R}}{R} \tag{3}$$

$$\begin{cases} R = R_o, t = 0 \\ \dfrac{dR}{dt} = 0, t = 0 \end{cases}$$

where,

- R = Radius of the bubble, *um*
- ρ = Density of the oil phase, Kg/m^3
- P_g = Internal pressure of the bubble, *Mpα*
- P_i = The pressure of outer boundary, *Mpα*
- σ = Surface tension, *N*/*m*
- u = The viscosity of oil phase, *mpα.s*
- t = The time, *s*
- R_o = Initial bubble diameter, *um*

The diffusion equation is as follows:

The following equation can be deduced from the Fick's first law of diffusion and the Fick's second law of diffusion and the following equation simultaneously comprises the initial and boundary conditions:

$$\begin{cases} \frac{\partial C}{\partial t} = D(\frac{\partial^2 C}{\partial^2 r} + \frac{2}{r}\frac{\partial C}{\partial r}) - (\frac{R}{r})^2 \frac{dR}{dt}\frac{\partial C}{\partial r}, r \geq R \\ C = C_o, t = 0, r \geq R \\ P_G = f(C), r = R \end{cases} \quad (4)$$

where,

C = The concentration of dissolved gas in the oil phase, m^3/m^3

D = The diffusion coefficient of gas in the oil phase, m^2/s

r = The distance to the bubble center in the oil phase, *um*

C_o = The initial concentration of dissolved gas in the oil phase, m^3/m^3

In heavy oil, as the diffusion speed of the gas in the oil phase is slow and the initial surface area in the bubble growth is small, the mass flux entered into the bubble is small, the speed of bubble growth is slow and the bubble growth is carried out in a long period of time, which is in line with the bubble dissipating time of the oil sample collected from the oil well of heavy oil cold production in Canada.

Bubble Number:

Supersaturation calculation of oil phase: When the pressure of the unsaturated crude oil in porous medium is below the pressure of the bubble point, the crude oil is shown in a supersaturation state. In the process, the crude oil is usually transited to supersaturation state from the unsaturated state before forming the bubbles. The super saturation is the difference between the equilibrium pressure and actual pressure (Li and Yortsos, 1991).

The supersaturation S is defined as follows:

$$S(t) = P_e(t) - P(t), S \geq 0 \quad (5)$$

In which,

P_e = Equilibrium pressure, $P_e = P_g$

P = Ppressure of oil phase

In the mixed phase of oil and gas:

$$P_e(t) \approx P_b - \beta(V - V_b), \beta > 0$$

In which,

V_b = The volume of the mixed phase of oil and gas in the pressure of the bubble point

For a single-phase system:

$$\beta = 0 \text{ and } P_e(t) \approx P_b$$

Bubble number calculation of oil phase: The bubble formation frequency of different supersaturations is calculated by means of the relational expression of bubble nucleation in the porous medium oil phase obtained by wood (1953):

$$J = 9 \times 10^{-3} \exp(-\frac{16.5}{\Delta P^2}) \quad (6)$$

Namely:

$$J = 9 \times 10^{-3} \exp(-\frac{16.5}{(P_b - \beta(V - V_b) - p(t))^2}) \quad (7)$$

For a single-phase system, namely the foam oil phase, the calculation formula for the bubble formation frequency of different supersaturations in the oil phase is as follows:

$$J = 9 \times 10^{-3} \exp(-\frac{16.5}{(P_b - p(t))^2}) \quad (8)$$

According to the curve of bubble number in the oil phase (Fig. 1) , it can be seen that the increase of bubble number in the initial stage is slow, the increase in the middle stage is rapid, the increase in the last stage is slow and the number of the bubble does not change.

Properties of foam oil:

Density calculation of foam oil: The total bubble volume in the oil phase of different pressures is as follows:

$$v_{bubbles} = \sum_{1}^{n\_bubbles} (\frac{4}{3}\pi R_i^3) \quad (9)$$

The density of the foam oil in a microscopic model is as follows:

$$x = v_{bubbles} / (v_{oil} + v_{bubbles}) \quad (10)$$

$$\rho_f = \rho_g x + \rho_o (1 - x) \quad (11)$$

Viscosity calculation of foam oil: For the viscosity of foam oil, the debate is greater, specifically some scholars believe that the viscosity of foam oil is reduced due to the reduction of the density there of and therefore the flow performance of the foam oil is stronger. Another part of the foreign scholars believe that the viscosity of foam oil is slightly larger than that of the crude oil of original saturated dissolved gas through laboratory experiments.

In the study, the viscosity of foam oil is calculated by using Ialam-Chakma (1990) model (Sun, 2005):

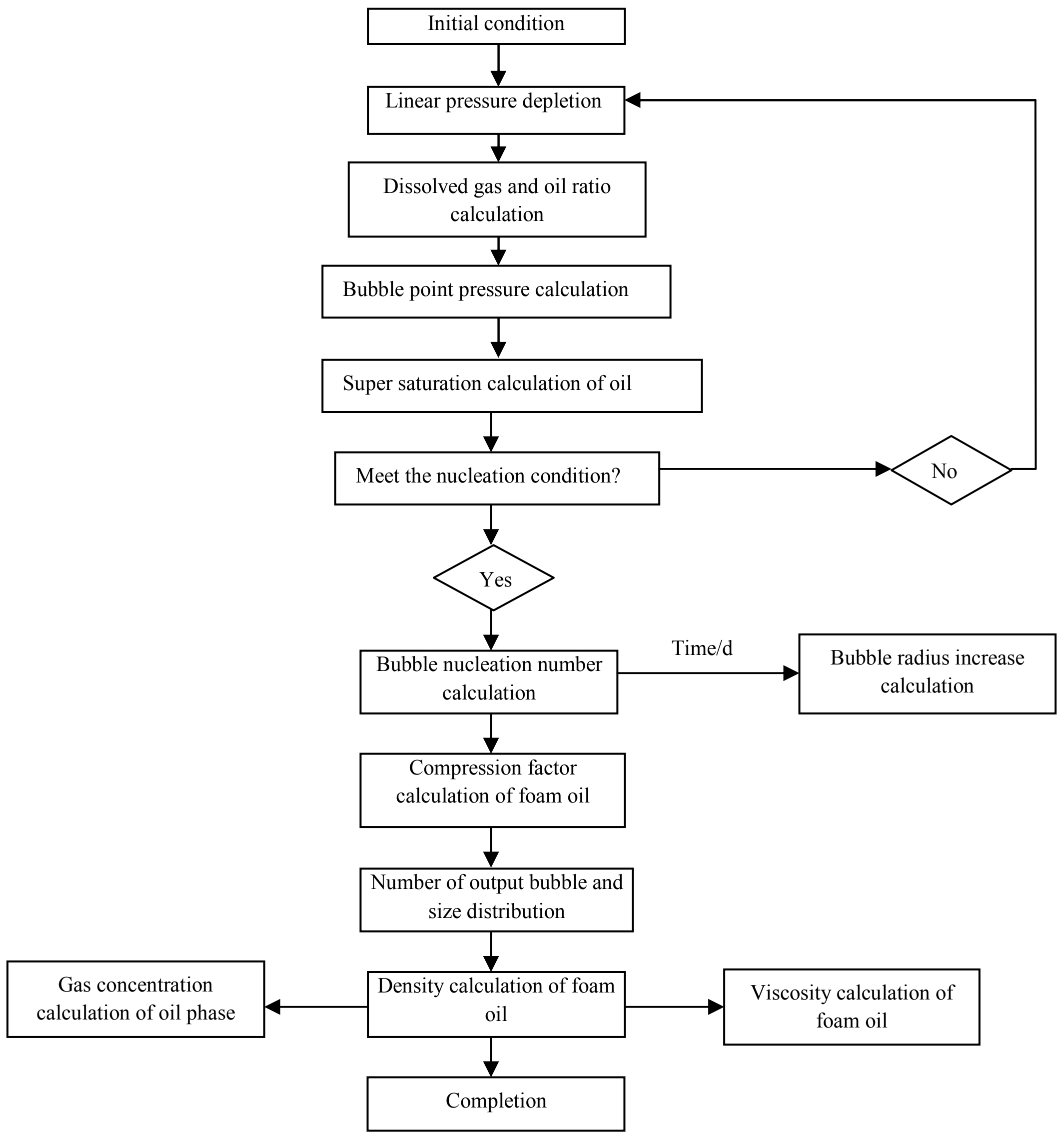

Fig. 2: Calculation flowchart

Ialam and Chakma measure the viscosity of the pre-formed foam oil by using the capillary of which the length is 2 m and the diameter is 2 mm and they believe that the total viscosity of foam oil may be related to the viscosity of the gas dispersed therein, namely:

$$u_f = u_g{}^x u_o{}^{(1-x)} \tag{12}$$

where,

x	=	The volume factor of the gas
u_o and u_g	=	The viscosity of the oil phase and gas phase
u_f	=	The total viscosity of the from oil

Flowchart for properties calculation of foam oil (Fig. 2):

Calculation results: By model calculations (Fig. 3 and 4), the viscosity and density of foam oil are in a declining tendency with the reduction of pressure. In the initial stage, the decrease of the viscosity and density is slow as the volume of the bubble is small and the number of the bubble is small; in the middle stage, a large number of bubbles are generated, the viscosity and density are decreased rapidly; and in the last stage, the number of bubbles in the oil phase tends to stabilization, the growth of the bubble also tends to mild and the viscosity and density of the foam oil are almost not decreased.

Establishment of inflow performance model: The flow equation of single-phase inflow performance is as follows:

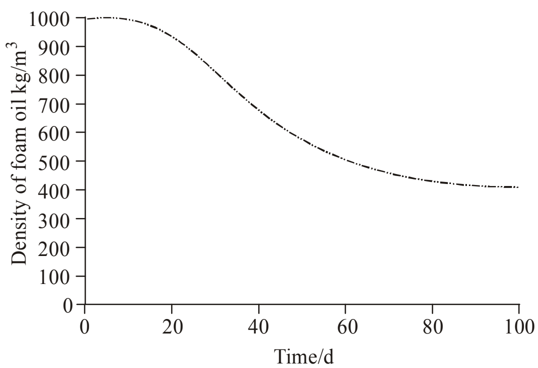

Fig. 3: Density curve of foam oil

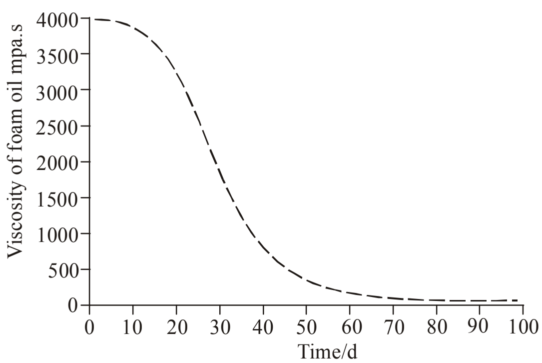

Fig. 4: Viscosity curve of foam oil

$$m_o(t) = \frac{2\pi hk}{\ln\frac{re}{rw} - \frac{1}{2}} \int_{pwf}^{pe} \frac{k_o \rho_o}{\mu_o} dp \tag{13}$$

The flow equation of the gas phase is as follows:

$$m_g(t) = \frac{2\pi hk}{\ln\frac{re}{rw} - \frac{1}{2}} \int_{pwf}^{pe} \frac{k_g \rho_g}{\mu_g} dp \tag{14}$$

The total flow equation based on the linear simultaneous formulas above is as follows:

$$m\ (t) = \frac{2\pi hk}{\ln\frac{re}{rw} - \frac{1}{2}} \int_{pwf}^{pe} (\frac{k_o \rho_o}{\mu_o} + \frac{k_g \rho_g}{\mu_g}) dp \tag{15}$$

For the foam oil, it is a single phase, in which the density and viscosity of the foam oil are changed with the pressure as the number and volume of the bubble in the oil phase are increased while reducing the pressure. The curve for the density and viscosity change of the foam oil with the pressure is obtained by establishing bubble growth models and nature models of the foam oil.

Therefore, the flow equation of the foam oil in the correction of a microscopic model is as follows:

$$Q_{fo}(t) = \frac{2\pi hk}{[\ln\frac{re}{rw} - \frac{1}{2}]} \frac{1}{\rho_{fo}(p)\big|_{pwf}} \int_{pwf}^{pe} (\frac{k_{fo}\rho_{fo}(p)}{\mu_{fo}(p)}) dp \tag{16}$$

RESULTS AND DISCUSSION

The IPR curves of the foam oil of different viscosities are compared with the IPR curves of the conventional oil reservoirs. (Fig. 5)

For conventional heavy oil, the dissolved gas in the oil phase will be released to form a continuous gas phase when the pressure of the oil phase is lower than that of the bubble point, wherein the formation of the continuous gas affects the flow of the oil phase, the yield is decreased and therefore the IPR curve of the conventional heavy oil is shown in upwards convex tendency; for the foam oil, the dissolved gas will prevents from releasing and existing in the oil phase in the form of a large number of dispersed micro-bubbles when the pressure of the oil phase is lower than that of the bubble point and these dispersed bubbles will not fuse or rupture, the IPR curve of the foam oil will increase the yield of the crude oil as the emergence of bubbles; and the IPR curve is shown in downwards curve tendency which is opposite to the conventional tendency.

Simulate foam oil reservoirs via cmg-start models so as to obtain inflow performance curve of foam oil reservoirs.

For the oil well of foam oil flow, establish foam oil flow reservoir model, conduct production upon rated output and obtain flowing bottom whole pressure, average reservoir pressure and oil yield, select certain average pressure and record flow pressure and oil yield at that time to use as ordinate and abscissa for the first point. Conduct the production upon another yield and find the flow pressure and oil yield under the same average pressure as the ordinate and abscissa for the second point. The flow performance curve of foam oil well can be obtained upon a series of oil yield simulation.

As a matter of the comparison between simulation result and the simulation established, we can realize that:

- For the flow performance curve of foam oil well upon micro model, their tendency is quite similar by comparison with the result of CMG-STARS. It is clear that the curve upon theoretical model and mathematical model is significantly different from the curve of conventional oil reservoirs, especially extremely low flow pressure
- The inflow performance curve of oil well upon CMG-STARS simulation is a little different from IPR curve upon theoretical model established by us for the bubble broken is not considered in theoretical model. Consequently, the curve upon

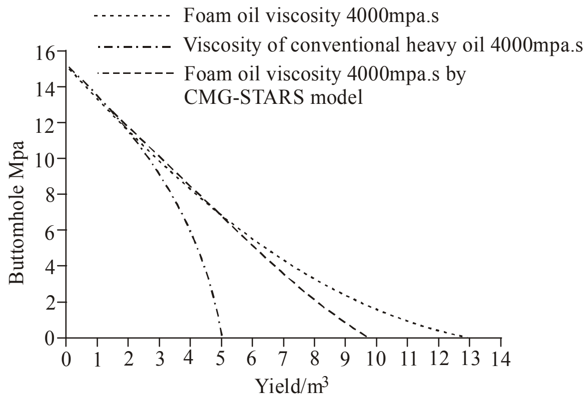

Fig. 5: IPR curves of foam oil and conventional oil reservoirs

theoretical model has obvious down jog and the error occurs to some extent.

CONCLUSION

- In the foam oil appeared in the cold production process of heavy oil, the formation and growth of the bubble have important impacts on the nature of the foam oil and affect the development performance of the foam oil
- By model calculations, the IPR curves of foam oil in heavy oil cold production and the IPR curves of conventional model calculation are quite different and the curves are shown in opposite tendencies, which are in line with the development characteristics foam oil
- The IPR curve upon theoretical model is consistent with that upon CMG-STARS model in tendency, but there is still some difference for the bubble broken is not considered in theoretical model. Consequently, the curve upon theoretical model has obvious down jog and the error occurs to some extent so that the model shall be modified further.

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