New analytical equations for productivity estimation of the cyclic CO₂-assisted steam stimulation process considering the non-Newtonian percolation characteristics

Fengrui Sun^{1,2,3} · Yuedong Yao^{1,2,3} · Guozhen Li³

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Abstract

The research course in the estimation of productivity of cyclic steam stimulation wells can be divided into three stages: (a) the mobility of heavy oil in the cold area is neglected, (b) the mobility of heavy oil in the cold area is considered—however, it is Newtonian fluid seepage, and (c) it is conserved as non-Newtonian fluid seepage in the cold area. However, the distribution of the value of starting pressure gradient in the heated area where heavy oil is still non-Newtonian fluid is neglected. In this paper, a new model is developed for productivity estimation of cyclic steam stimulation wells with consideration of the non-Newtonian fluid flow behaviors in the heated area where the temperature is higher than the turning point. New percolation equations are developed based on the new proposed concept of “the transition region” in the heated area. The results show that: (1) when the non-Newtonian fluid characteristic is neglected, the predicted results from the new model match the results from the numerical simulator perfectly, and (2) in oil field, the non-Newtonian fluid characteristic cannot be neglected. When the non-Newtonian fluid characteristic is considered in the model, the average oil production in each cycle can match the filed data better than Yang et al.’s model. This new model laid a basic reference for oil companies and researchers involved in the area when they are designing the well pattern, spacing or estimating the productivity of oil wells.

Keywords Heavy oil · Cyclic CO₂-steam stimulation · Productivity estimation · Non-Newtonian fluid · Transition region

Introduction

The effect of CO₂ on the climate change has already attract the attention of researchers (Jacobson 2009; Li et al. 2017). Given the fact that CO₂ sequestration will cost a lot, effective methods of using CO₂ for improving oil recovery efficiency are being studied in oil companies and researchers (Wang et al. 2012; Boot-Handford et al. 2014). Capture

and sequestration of CO₂ has been proved to be effective in carbon reduction (Li et al. 2017). In field practice, CO₂ has already brought economic benefit to oil companies (Dai et al. 2013; Middleton et al. 2015).

At present, the development of heavy oil is showing more important (Sun et al. 2017a, b, c, d, e, f, g, h, i, j), and the reaction of heavy oil with different chemical substances is the focus of research (Sun et al. 2018a, b, c, d, e, f). Similar to the other thermal engineering (Sheikholeslami 2017a, b, c, d, 2018a, b, c, d, e), thermal study is an important direction of heavy oil research (Sun et al. 2018g, h, i, j, k, l, m, n). For the study of cyclic CO₂-assisted steam stimulation, it is found out that when the CO₂ is dissolved in heavy oil, the oil volume will has an increase. Accordingly, the oil viscosity decreases and the oil percolation capacity increases (Welker 1963; Simon 1965; Chung et al. 1988; Li 2015). Another oil recovery mechanism of CO₂ injection is reducing the interfacial tension by extraction of light components from the crude oil (Zheng et al. 2013; Zhang et al. 2014a, b; Seyyedsar et al. 2016; Wang et al. 2017a, b; Rostami et al. 2017). Based on

✉ Fengrui Sun
13126682711@163.com

✉ Yuedong Yao
yaoyuedong@163.com

¹ State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum-Beijing, Beijing 102249, People’s Republic of China

² College of Petroleum Engineering, China University of Petroleum-Beijing, Beijing 102249, People’s Republic of China

³ China University of Petroleum-Beijing, Beijing 102249, People’s Republic of China

these promising advantages of CO₂, CO₂ has always been selected as the auxiliary for heavy oil EOR.

Thermal injection for heavy oil recovery has been widely adopted in oil field and has been proved effective and economically efficient (Fengrui et al. 2018a, b, c; Zhou et al. 2013; Guo et al. 2016; Doranehgard and Siavashi 2018; Bordeaux Rego et al. 2017). Among those thermal methods, cyclic steam stimulation, steam-assisted gravity drainage, steam flooding and burning oil layer are the widely used ones (Pujol and Boberg 1972; Coats et al. 1973; Meldau 1979; Matthews 1982; Vittoratos et al. 1990; Beattie et al. 1991; Supernaw and Savage 1992; Wu and Marschke 1992; Mokrys and Butler 1993; Butler 1985, 1994; Hedlin et al. 2001; Dezzani and Al-Dousari 2001; Smith et al. 2004; Du et al. 2008; Luo and Cheng 2004; Luo et al. 2005; Zhao et al. 2008; Coskuner 2009). In this paper, a new model is proposed to describe the flow behaviors of heavy oil in reservoirs after a certain amount of CO₂ and steam is injected into the oil layer.

In the case of cyclic steam stimulation, it has been widely used in both onshore and offshore heavy oil reservoirs (Boberg and Lantz 1966; Boberg 1988; Farouqali and Speaime 1976; Burger et al. 1986; Xu et al. 2013; Yang et al. 2017). This is because steam with high temperature can reduce the viscosity of heavy oil to a satisfactory level (Hou et al. 2016). Second, steam huff and puff can effectively form the inter-well heat connection, which laid a foundation for the following steam flooding process (Zhang et al. 2014a, b; An et al. 2006).

To describe the cyclic steam stimulation process, a series of works were conducted. Marx–Langenheim (1959) proposed a model for estimating the heated radius based on the law of energy conservation. Based on the assumption of the heated region was a cylinder, Willman et al. (1961) proposed an improved model for calculating the radius of the heated area. Mandl–Volek (1969) proposed a concept of critical time, which improves the calculation precision of the model. These previous studies laid a solid foundation for later studies (Dou et al. 2007). However, these models assumed that the reservoir can be divided into two areas: the heated area and the unheated area. In the heated area, the temperature is equal to the steam temperature at well-bottom condition. In the unheated area, the temperature is equal to the initial reservoir temperature. In fact, the temperature is decreasing with the distance to well-bottom.

Li and Cheng (1998) and Li and Yang (2003) proposed models for heated radius calculation considering the temperature drop from well-bottom to unheated area, which laid a solid foundation for later studies (He et al. 2015). However, these models did not take the non-Newtonian characteristics of heavy oil into consideration. Yang et al. (2017, 2018) proposed a model for estimating the productivity of cyclic steam stimulation wells. However, this model did not take

the distribution of the starting pressure gradient in the heated area into consideration, which brings some error to the calculation results.

In this paper, a new model is proposed for estimating productivity of cyclic CO₂-steam stimulation wells. The effect of non-Newtonian percolation characteristics in the heated area on the productivity has been taken into consideration.

Model description

Model assumption

To establish the model, some basic assumptions are listed below:

- During the production period, the injected CO₂-steam has been condensed to hot water and the hot water exists only in the Newton fluid area. That is to say, it is two-phase flow in the Newton fluid area while it is single-phase flow in the non-Newton fluid area (Yang et al. 2017, 2018).
- When the CO₂-steam injection period is finished, the reservoir can be divided into three sub-zones: the Newton fluid area, the Newton and non-Newton transition area and the non-Newton fluid area.

Steam injection period

Based on previous works, the reservoir can be divided into three areas during the CO₂-steam injection period, as shown in Fig. 1 (He et al. 2015; Yang et al. 2017, 2018).

Fig. 1 The distribution of latent heated area, sensible heated area and unheated area during the CO₂-steam injection process (He et al. 2015; Yang et al. 2017, 2018)

The latent heated area

The temperature is kept unchanged in the latent heated area. Based on the M–L equation, the energy balance equation in the latent heated area can be expressed as (Marx–Langenheim 1959):

$$i_s x h_s = 2 \int_0^t \frac{\lambda_s (T_s - T_r)}{\sqrt{\pi \alpha_s}} \cdot \frac{dA}{d\delta} + M_r h (T_s - T_r) \frac{dA}{dt}. \quad (1)$$

Using the Laplace transform, the area of the latent heated area can be given as:

$$A(t)_s = \frac{i_s x h_s M_r h \alpha_s}{4 \lambda_s^2 (T_s - T_r)} \cdot \left[e^{\text{erfc}(\sqrt{t_D})} + 2 \sqrt{\frac{t_D}{\pi}} - 1 \right], \quad (2)$$

where $t_D = \frac{4 \lambda_s^2}{M_r^2 h^2 \alpha_s} \cdot t_{inj}$.

The radius of the latent heated area can be expressed as (Marx–Langenheim 1959; He et al. 2015; Yang et al. 2017, 2018):

$$r_s = \sqrt{\frac{i_s x h_s M_r h \alpha_s}{4 \lambda_s^2 \pi (T_s - T_r)}} \cdot \sqrt{\left[e^{\text{erfc}(\sqrt{t_D})} + 2 \sqrt{\frac{t_D}{\pi}} - 1 \right]}, \quad (3)$$

where i_s denotes the mass injection rate, kg/h; x denotes the steam quality, dimensionless; h_s denotes the steam enthalpy, kcal/kg; h denotes the thickness of the reservoir, m; α_s denotes the thermal diffusivity, m²/h; λ_s denotes the thermal conductivity of rock, kcal/(h m²); t_{inj} denotes the injection time, day; M_r denotes the heat capacity of reservoir rock, kcal/(m³ °C); T_r denotes the initial reservoir temperature, °C.

The sensible heated area

It is assumed that the temperature in the sensible heated area decreases with distance to the well-bottom, which can be expressed as (He et al. 2015; Yang et al. 2017, 2018):

$$T(r) = \frac{T_s - T_r}{r_s - r_h} r + \frac{T_r r_s - T_s r_h}{r_s - r_h}. \quad (4)$$

Based on the energy balance equation, the energy balance equation can be given as:

$$i_s [C_w (T_s - T_r)] = 2 \int_0^t \frac{\lambda_s [T(r) - T_r]}{\sqrt{\pi \alpha_s (t - \delta)}} \cdot \frac{dA}{d\delta} + M_r h [T(r) - T_r] \frac{dA}{dt}. \quad (5)$$

Similarly, the radius of the sensible heated area can be obtained using the Laplace transform, which can be expressed as (He et al. 2015; Yang et al. 2017, 2018):

$$r_h = \frac{1}{2} \left\{ -r_s + \left\{ r_s^2 + 4 \left[2r_s^2 + \frac{3C}{\pi(T_s - T_r)} \right] \right\}^{\frac{1}{2}} \right\}, \quad (6)$$

Where, $C = \frac{1}{4 \lambda_s^2} \{ i_s [C_w (T_s - T_r)] M_r h \alpha_s \} \cdot [e^{\text{erfc}(\sqrt{t_D})} + 2 \sqrt{t_D/\pi} - 1]$ where C_w denotes the heat capacity of water, cal/(kg °C).

Reservoir pressure

When the CO₂-steam mixture system is injected into the oil layer, the reservoir pressure will increase due to volume increase and thermal expansion. When the injection process is finished, the average reservoir pressure can be expressed as (He et al. 2015; Yang et al. 2017, 2018):

$$p_{e1} = p_e + \frac{G_i B_w}{1000 \times N B_o C_e} + \frac{N_{oh} (T_{navg} - T_i) \beta_e}{1000 \times N C_e}, \quad (7)$$

where p_e denotes the reservoir pressure before the CO₂-steam is injected, MPa; N denotes the reserves of total fluid in the formation, m³; G_i denotes the steam volume in reservoir condition, m³; C_e denotes the comprehensive compression coefficient, MPa⁻¹; β_e denotes the comprehensive thermal expansion, 1/°C; N_{oh} denotes the initial reserves of oil in the formation, m³; T_{navg} denotes average temperature in the Newtonian area, °C.

The soak and production period

The soak period

Yang et al. (2017, 2018) proposed a model for estimating the productivity of cyclic steam stimulation wells. In their work, the reservoir was divided into three sub-areas, as shown below (Yang et al. 2017, 2018) (Fig. 2).

Fig. 2 The distribution of Newtonian and non-Newtonian fluid in the reservoir (Yang et al. 2017, 2018)

Fig. 3 The distribution of Newtonian region, transition region, and non-Newtonian fluid in the reservoir

In fact, the non-Newtonian fluid area can be divided into two sub-areas, as shown in Fig. 3. It is observed that there exists a transition region in the heated area.

The production period

The percolation equations for the transition region can be expressed as:

$$Q_w = \frac{2\pi K K_{rw} h}{\mu_w} \cdot \frac{p_e - p_{wf} - \lambda_1(r_h - r_n) - \lambda_0(r_e - r_h)}{\ln \frac{r_n}{r_w} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oh} \ln \frac{r_h}{r_n} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oc} \ln \frac{r_e}{r_h}} \quad (8)$$

$$Q_o = \frac{2\pi K K_{ro} h}{\mu_o} \cdot \frac{p_e - p_{wf} - \lambda_1(r_h - r_n) - \lambda_0(r_e - r_h)}{\ln \frac{r_n}{r_w} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oh} \ln \frac{r_h}{r_n} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oc} \ln \frac{r_e}{r_h}} \quad (9)$$

$$Q_l = 2\pi h \left(\frac{K K_{rw}}{\mu_w} + \frac{K K_{ro}}{\mu_o} \right) \cdot \frac{p_e - p_{wf} - \lambda_1(r_h - r_n) - \lambda_0(r_e - r_h)}{\ln \frac{r_n}{r_w} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oh} \ln \frac{r_h}{r_n} + \left(\frac{K_{ro}}{\mu_{oh}} + \frac{K_{rw}}{\mu_w}\right) \mu_{oc} \ln \frac{r_e}{r_h}} \quad (10)$$

where Q_w denotes the water production rate, m^3/d ; Q_o denotes the oil production rate, m^3/d ; Q_l denotes the liquid production rate, m^3/d .

The percolation equations for the other regions can be found in Yang et al.'s (2017, 2018) work.

Model comparison

Neglecting the non-Newtonian fluid characteristic

The basic calculation results used in the calculation can be found in Yang et al. (2017, 2018) work. The predicted results from the new model are compared with numerical simulator

Fig. 4 Comparison of the predicted results from different models neglecting the non-Newtonian fluid characteristics

and previous models. The comparison results are shown in Fig. 4. It is observed that the results from the new model show good agreement with the results from the numerical simulator when the non-Newtonian fluid characteristic is neglected.

Considering the non-Newtonian fluid characteristic

Besides, the predicted results from different models are compared against field data (Yang et al. 2017, 2018), as shown in Table 1. It is observed that the predicted results from the new model are in agreement with field data, which proves correctness of the new model.

Conclusion

In this paper, a new model is proposed for calculating productivity of cyclic CO_2 -steam/steam/superheated steam/thermal fluid stimulation wells. Some meaningful conclusions are listed below:

1. When the non-Newtonian fluid characteristic is neglected, the predicted results from the new model match perfectly with the results from the numerical simulator.
2. In oil field, the non-Newtonian fluid characteristic cannot be neglected. When the non-Newtonian fluid characteristic is considered in the model, the average oil

Table 1 Predicted results with consideration of the non-Newtonian fluid characteristic

	Numerical simulator	Yang et al. (2017, 2018)	New model	Field data (Yang et al. 2017, 2018)
Average oil production, first cycle, m ³ /d	11.85	9.31	9.39	9.5
Average oil production, second cycle, m ³ /d	8.93	7.95	7.76	7.7
Average oil production, third cycle, m ³ /d	7.72	6.55	6.41	6.3

production in each cycle can match with the filed data better than previous model.

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