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An analytical model of SAGD process considering the effect of threshold pressure gradient

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Abstract. An analytical model is proposed for the development of super-viscous oil deposits by the method of steam-assisted gravity drainage, taking into account the nonlinear filtration law with the limiting gradient. The influence of non-Newtonian properties of oil on the productivity of a horizontal well and the cumulative steam-oil ratio are studied. Verification of the proposed model based on the results of physical modeling of the SAGD process was carried out.

1. Introduction

Steam-assisted gravity drainage (SAGD) is an efficient method for high-viscosity oil and natural-bitumen recovery based on steam injection and horizontal well technology [1]. Currently SAGD is used on heavy oil deposits in Canada, Venezuela and China. In Russia, the SAGD has been successfully applied on the Ashal′chinskoe field in the Republic of Tatarstan (since 2006) and the Yaregskoe field in the Republic of Komi.

The SAGD method uses a series of pairs of injection-producing horizontal wells (Figure 1). The steam chambers formed above each pair of wells, reaching the top of the formation, propagate horizontally until they coalescence [1, 2]. As the angle of inclination of the boundary of the steam chamber decreases, the rate of drainage decreases. At the final stage of the steam assisted gravity drainage in the inter-wellbore space stagnant zones are formed, not covered by the impact. The formation of such zones is a consequence of the manifestation of non-Newtonian properties of super viscous oils.

The efficiency of a SAGD project depends strongly on bitumen-production rate, recovery factor, and cumulative steam-oil ratio (CSOR). Hence, an accurate CSOR prediction is the key to the success of a SAGD project, particularly for the planning and engineering design phases.

Butler [1, 2] and Reis [3] assume that the shape of the steam chamber in a plane perpendicular to the wells is close to a triangle whose vertex coincides with the producing horizontal well. An analytical model of steam-assisted gravity drainage was proposed in [5], which describes the main stages of the evolution of the steam chamber: its growth up to the top of the formation, horizontal propagattion and expansion of the steam chamber in the direction of the bottom of the formation. In these works, the horizontal well production rate was calculated taking into account the Darcy law.

Unlike conventional oil, heavy oil and bitumen can be considered as a non-Newtonian (Bingham) fluid which has a threshold pressure gradient. However, the current analytical models as well as numerical simulation of SAGD process neglect the non-Newtonian flow behavior of heavy oil. In this work, a new analytical model based on the Butler’s SAGD theory and filtration law with a threshold pressure gradient is developed and analyzed. This model allows to predict the oil flow rate and CSOR during all periods of steam chamber’s growing.

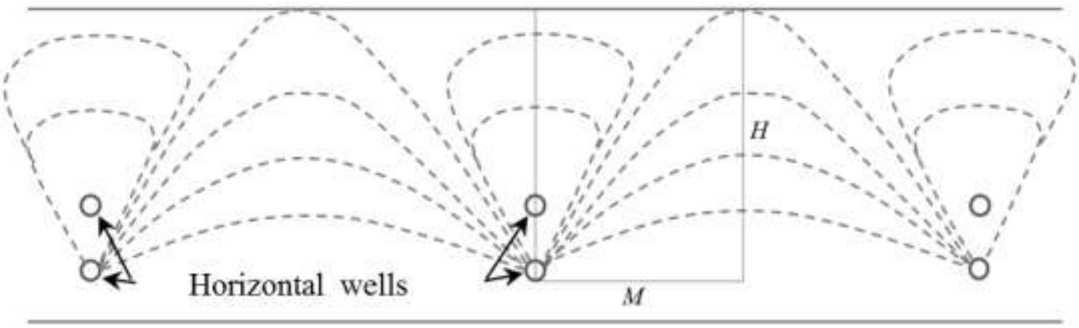


Fig. 1. SAGD scheme.

2. Analytical solution

It is assumed that oil is drained due to gravity according to a nonlinear filtration law with a threshold pressure gradient:

$$w = \begin{cases} \frac{k}{\mu}[\rho_0 g \sin\ \theta - \gamma], \left|\rho_0 g \sin\ \theta\right| \geq \gamma, \\ 0, \left|\rho_0 g \sin\ \theta\right| < \gamma, \end{cases} \quad (1)$$

where w – is the filtration velocity; ρ_0 – density of oil; θ – the angle of inclination of the boundary of the steam chamber; k – formation permeability; γ – characteristic value of the threshold pressure gradient for oil behind the contact surface of the steam chamber. The non-Newtonian nature of the flow of super-viscous oils is due to the high content of asphaltenes and high-molecular paraffins. One of the peculiarities of super-viscous oils is that they begin to "move" only after reaching the limiting pressure gradient γ, necessary to overcome the shear stress threshold τ_0. It has been experimentally established that the dependence γ vs τ_0 is of the form [4, 6]:

$$\gamma = \alpha \frac{\tau_0}{\sqrt{k}},$$

where $\alpha = (162 \div 180) \cdot 10^{-4}$.

Based on the law of conservation of mass and the nonlinear filtration law with threshold pressure gradient (1), an analytical model of steam assisted gravity drainage (2) - (4) is obtained, which describes the main stages of the steam chamber evolution in the element of super-viscous oil deposit development:

1. During the period of growth of the steam chamber, the production rate of a horizontal well varies according to a power law:

$$q(t) = 2L\left(\frac{3}{8}\text{tg}\,\theta^*\phi\Delta S_0\right)^{\frac{1}{3}}\left(B - \frac{C}{\sin\ \theta^*}\right)^{\frac{2}{3}} t^{\frac{1}{3}}, \quad (2)$$

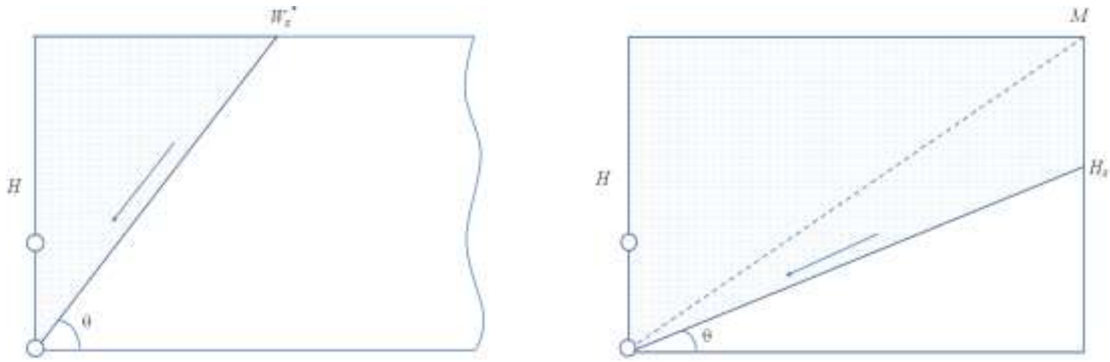
where $B = \frac{k\alpha g}{a\nu_s m}$, $C = \frac{k\alpha\gamma}{a\nu_s\rho_0 m}$, H – effective thickness of the formation (Fig. 1, Fig. 3a); L – length of horizontal well; ΔS_0 – the difference between the initial and final oil saturation; ϕ – porosity; α – thermal diffusivity; ν_s – kinematic viscosity of oil at the temperature of injected steam; g – acceleration of gravity; m – dimensionless parameter; $a = 0.4$ – an empirical constant [4]. According to Butler's experimental data, the angle θ^* formed by the boundary of the steam chamber and the bottom of the formation remains unchanged during the period of growth of the steam chamber to the top of the reservoir and amounts to ≈ 60 degrees [2].

The height of the steam chamber during the growth period is given by:

$$h(t) = \left(\frac{3}{4}\,\mathrm{tg}\,\theta^*\right)^{\frac{2}{3}} \left(\frac{2B}{\phi \Delta S_0} - \frac{2C}{\phi \Delta S_0 \sin\,\theta^*}\right)^{\frac{1}{3}} t^{\frac{2}{3}}. \quad (3)$$

The time the steam chamber reaches the top of the formation is determined from equation (3). The width of the steam chamber will then be $W_s^* = \dfrac{H}{\mathrm{tg}\,\theta^*}$.

When $\gamma = 0$ expression (2) is analogous to Butler's formula for estimating the production rate of a horizontal well during the growth of the steam chamber to the top of the formation [2].



a *b*

Fig. 2. Steam chamber scheme.

2. During the expansion of the steam chamber in horizontal direction, the production rate of a horizontal well is determinated from the solution of the ordinary differential equation with respect to the width of the steam chamber W_s:

$$q(t) = 2LA\frac{dW_s}{dt},\ \frac{dW_s}{dt} = \left(\frac{B}{A} - \frac{C}{A\sin(\theta)}\right)^{\frac{1}{2}},\ W_s^* < W_s \le M\ , \quad (4)$$

where $A = \dfrac{\varphi \Delta S_0 H}{2}$, $B = \dfrac{k\alpha g}{a\,v_s m}$, $C = \dfrac{k\alpha\gamma}{a\,v_s \rho_0 m}$, $\theta = \mathrm{arctg}\,\dfrac{H}{W_s}$, M – half the distance between neighbor pairs of horizontal wells (Figure 1, Figure 3 b). When $\gamma = 0$ expression (4) coincides with the Reis formula [3]. In this case, the horizontal well rate during the horizontal expansion of the steam chamber remains constant.

3. During the period of expansion of the steam chamber in the direction of the bottom of the formation, the flow rate of the horizontal well is determined from the solution of the ordinary differential equation with respect to H_s:

$$q(t) = 2LA\frac{dH_s}{dt},\ \frac{dH_s}{dt} = -\left(\frac{B \cdot H_s}{A} - \frac{C}{A\cos(\theta)}\right)^{\frac{1}{2}},\ H \ge H_s \ge H_s^*, \quad (5)$$

where $H - H_s$ – is the length of the common boundary of adjacent steam chambers (Figure 3b), $A = \dfrac{\varphi \Delta S_0 M}{2}$, $B = \dfrac{k\alpha g}{a\,v_s m M}$, $C = \dfrac{k\alpha\gamma}{a\,v_s \rho_0 m}$, $\theta = \mathrm{arctg}\,\dfrac{H_s}{M}$, $H_s^* = M\mathrm{tg}(\theta_*)$ – height of the stagnant zone.

The limiting angle of inclination of the steam chamber boundary $\theta_* = \arcsin\left(\frac{\gamma}{\rho_0 g}\right)$. When the steam chamber reaches its limit position, the SAGD process is terminated. Note that when $\gamma = 0$ the flow rate of the horizontal well decreases linearly during this period of the steam chamber expansion[5].

The filtration law with the threshold pressure gradient (1) is an idealization of the filtration anomalies, and the value of γ is a dynamic characteristic, depending on the temperature. To take into account possible "subthreshold" flows, instead of the filtration law with the threshold pressure gradient (1), we also considered the piecewise linear law of filtration [6]:

$$w = \begin{cases} \frac{k(\theta)}{\mu}\left[\rho_0 g \sin\theta - \gamma\right], \left|\rho_0 g \sin\theta\right| \geq \frac{\gamma}{1-\varepsilon}, \\ \frac{\varepsilon k(\theta)}{\mu}\rho_0 g \sin\theta, \left|\rho_0 g \sin\theta\right| < \frac{\gamma}{1-\varepsilon}, \end{cases} \tag{6}$$

where $\frac{\varepsilon k}{\mu}$ – "subthreshold" mobility.

The main indicator of the effectiveness of the steam-thermal effect is the coefficient of the cumulative steam-oil ratio, which is defined as the ratio of the cumulative steam flow S to the cumulative oil production O [7]:

$$CSOR = \frac{S}{O}. \tag{7}$$

The cumulative steam flow S is calculated as the ratio of cumulative heat U_t to the latent heat of steam condensation U_l. In turn, U_t is the sum of the heat in the steam chamber and the total loss of heat through the top of the formation and lateral boundary of the steam chamber. The heat of the steam chamber is given by:

$$U_c = F\Delta T C_{vr},$$

where F – the area of the steam chamber (Figure 3), ΔT – the temperature difference between the steam chamber and the formation, C_{vr} – the heat capacity of the formation.

The loss of heat through the top of the reservoir is expressed in the form [7]:

$$U_o = \frac{8}{3} W_s \Delta T \sqrt{\frac{k_t C_{vo} t}{\pi}},$$

where k_t and C_{vo} – is the thermal conductivity and heat capacity of the top. The loss of heat through the lateral boundaries of the steam chamber is one third of the heat loss through the top of the formation [7].

3. Results and Discussions

Fig. 3 shows the mass flow of oil obtained in the course of the experiment on the physical model of the SAGD process [2, 8], as well as the results of flow rate calculations by the proposed model (solid line) with the following parameters: k = 2.5 μm^2, φ = 0.39, ΔS_0 = 0.95, H = 0.21 m, L = 0.03 m, M = 0.175 m, α = 0.05 m^2 / day, ν_s = 9 m^2 / day, m = 3.6, γ = 0.001 MPa / m, ε = 0.05. The results of numerical calculations on the thermohydrodynamic simulator CMG STARS [8] are shown in Fig. 3 by the dotted line.

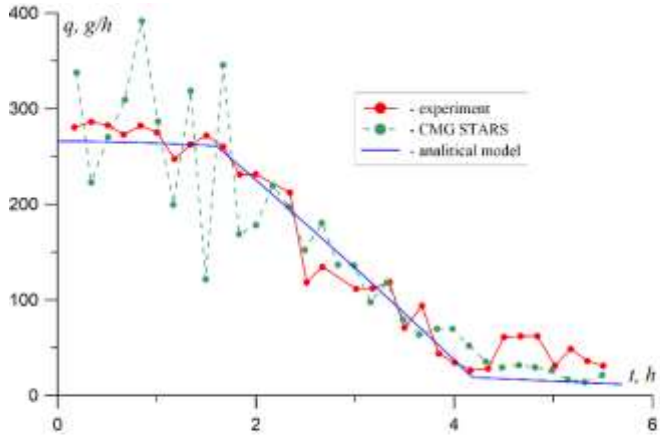


Fig. 3. Mass oil consumption by the proposed model, numerical model CMG STARS [8] and experimental data.

Fig. 4 shows the volumetric oil flow rate obtained during the experiment on the physical model of the SAGD process at low pressure of steam injection [9], as well as the results of production rate calculations by the proposed model with the following parameters: $k = 240$ μm^2, $\varphi = 0.35$, $\Delta S_0 = 0.9$, $H = 0.25$ m, $L = 0.08$ m, $M = 0.3$ m, $\alpha = 0.021$ m^2 / day, $\nu_s = 3.8$ m^2 / day, $m = 3$, $\gamma = 0.001$ MPa / m, $\varepsilon = 0.1$.

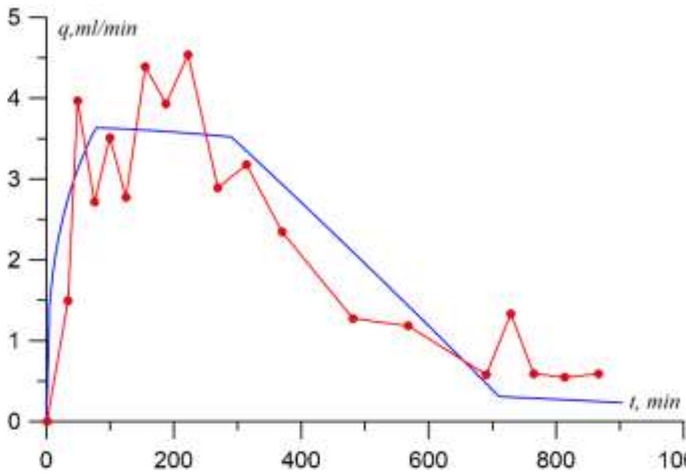


Fig. 4 Volumetric oil production rate according to the proposed model and experimental data [9].

Next, the reservoir model is considered with parameters [4]: $k = 2.5$ μm^2, $\varphi = 0.3$, $\Delta S_0 = 0.47$, $H = 25$ m, $L = 400$ m, $M = 50$ m, $\alpha = 0.03$ m^2/day, $\nu_s = 0.8$ m^2/day, $m = 4$, $\varepsilon = 0.01$. The results of calculations of the horizontal well rate, the cumulative steam-oil ratio and cumulative oil production for different values of the threshold pressure gradient γ_0 are presented in Fig. 5. As shown in Fig. 5 the threshold pressure gradient exerts a significant influence on the dynamics of the main SAGD indicators at all stages of growth of the steam chamber.

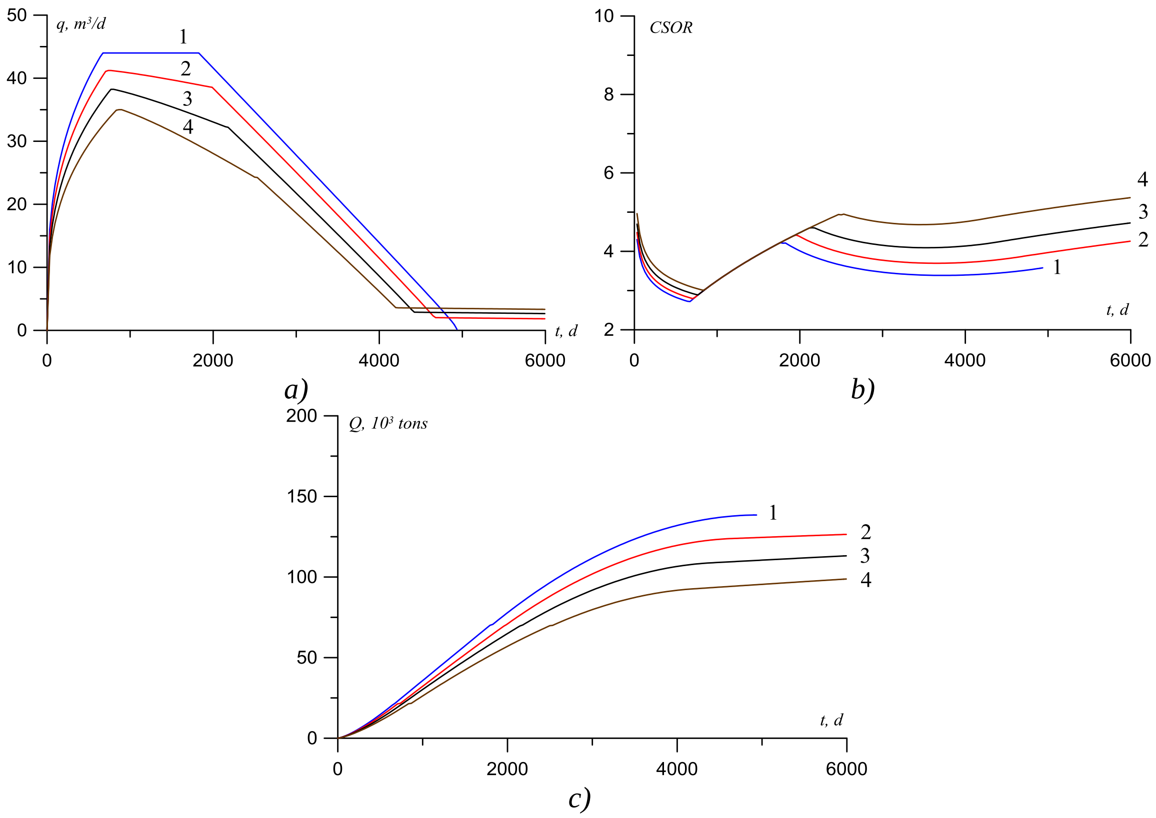


Fig. 5. Influence of the threshold pressure gradient on the horizontal well production rate (a), the cumulative steam oil ratio (b), cumulative oil production (c).
(1 - γ = 0 MPa, 2 - γ = 0.001 MPa, 3 - γ = 0.002 MPa, 4 - γ = 0.003 MPa, ε = 0.01)

The results indicate that the presence of threshold pressure gradient can significantly reduce the horizontal well productivity and increase the CSOR. Also, the threshold pressure gradient leads to a limiting angle of inclination of the steam chamber boundary and to the formation of an undrained zones between pairs of horizontal wells. It is shown that when the threshold pressure gradient is zero value, the proposed analytical model of SAGD process reduces to previous our model based on the Newtonian flow behavior of heavy oil [2].

4. Conclusions

An analytical model to predict the production rate of a horizontal well in SAGD process was developed by taking into account the effect of the threshold pressure gradient. The proposed model can predict the oil flow rate and CSOR during three periods of steam chamber’s growing, and was verified against experimental data on physical models. It shown that the threshold pressure gradient can significantly reduce the horizontal well productivity and increase the CSOR.

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