© L. N. SOKOLYUK, L. N. FILIMONOVA

orlubov@mail.ru, filimonovaln@mail.ru

UDC 532.546, 622.276

ANALYTICAL CYCLIC STEAM SIMULATION MODEL FOR HEAVY OIL RESERVOIRS

ABSTRACT. Estimated heavy oil reserves almost match those of conventional oil. Amongst the many methods of enhanced oil recovery used in heavy oil production steam injection is commercially successful. Promising new technologies such as cyclic steam stimulation (CSS) help to enhance recovery from heavy oil reservoirs. CSS is recommended on the basis of the geological characteristics of the reservoir containing viscous crude oil, the dynamics and the pressure at which the steam is injected. It is described an analytical model of CSS for a vertical well which was determined by the parameters of enhanced oil recovery on the basis of analytical evaluation of each of the above factors. Integrated evaluation methods are applied to calculate the dimensionless variables for each factor, which characterizes technological parameters of CSS. The results show that the higher the parameters' value the higher is the oil production for each well. The analytical model of steam injection to vertical wells was applied to calculate the optimal duration of injection, soaking and production at cyclic steam stimulation of the bottom-hole zone of a well. At that the net present value (NPV) characteristics were taken into account.

KEY WORDS. Cyclic steam injection, oil production, oil reservoir, heavy oil.

Until recently there was little interest to heavy oil fields, because developing these reserves was considered economically infeasible. Higher oil prices and traditional oil reserves depletion inspired new interest to the development of viscous crude oil reservoirs and application of many enhanced oil recovery methods. Thermal methods are considered the most effective at the development of heavy oil fields. In this approach, the crude oil in the formation is heated, which reduces its viscosity and increases its mobility. Thermal methods, however, require a lot of energy, which makes their feasibility disputable. Therefore, before recommending the said enhanced oil recovery method they carry out fastidious calculations to prove the profit [1–2]. Various models are used: numerical, analytical, phenomenological, statistical [3–5]. CSS is among one of the most often used enhanced oil recovery technologies.

This research develops an analytical model which describes CSS of bottom-hole zone of a vertical well and helps to calculate technological parameters and economic feasibility of this method, based on the net present value (NPV) [6]. The paper shows that the offered analytical model reduces the time required to calculate CSS parameters as compared to numerical calculations based on hydrodynamic simulators such as

Tempest MORE, Eclipse, CMG STARS, because it helps to computerize calculations of steam condensation time and fluid recovery time.

This model differs from the existing ones [3, 5, 7–9] in that it allows to calculate the temperature and the radius of the heated zone at the beginning of production regardless of the soaking duration.

In our model the steam is injected into a vertical well, drilled into a homogeneous oil reservoir layer of *h* thickness, *m* porosity, *k* permeability, which contains oil with μ viscosity. We do not take into account capillary effect and gravitation.

Steam injection technology consists of three stages. At the first stage the steam is injected into a well for a certain amount of time to heat a zone around the well. At the second stage the steam is fully condensed, and the oil from the colder layers of the reservoir soak the warmer layers. At the third stage fluid is produced; the thermal treatment of the layer increases well production rate. The length of the production stage is determined by the moment when the production rate decreases to the initial level, close to the level achieved without CSS [9].

The heat-balance equation at the first stage of steam injection is

$$((1-m)c_r\rho_r + mc_g\rho_g)h\Delta T\pi\frac{d(r^2-r_w^2)}{dt} = H - \alpha\Delta T\pi(r^2-r_w^2), \quad (1)$$

where $\Delta T = T_s - T_0$ is the difference between steam temperature and layer temperature (K); $H = q_n\rho_g(c_w\Delta T + l)$ is the injection rate (kJ per day); q_n — the volume of the heated steam injected (m^3 per day); ρ_g — steam density (kg/m^3); ρ_r — rock density (kg/m^3); c_g — steam thermal capacity (kJ/kg·K); c_r — rock thermal capacity (kJ/kg·K); l — latent heat of evaporation (kJ/kg); α — heat-transfer coefficient (kJ/(m^3 per day K)); h — layer thickness (m); r_w — well radius (m).

The equation (1) helps to calculate the steam-heated zone radius at the first stage of CSS as

$$r_s^2 = r_w^2 + \frac{\mathrm{H}}{\alpha\Delta T\pi}\left(1 - e^{-\frac{\alpha t}{\sigma m h}}\right) \quad (2)$$

At the second stage of steam condensation, the condensation front moves towards the well, its radius changing from r_k to r_w. We will describe the time, when the condensation front reaches the well as t_2^*.

After the condensation front reaches the well, the layer temperature can be calculated as

$$R_r h\pi(r_s^2 - r_w^2)\frac{d(T-T_0)}{dt} = -\alpha\pi(r_s^2 - r_w^2)(T-T_0), \quad (3)$$

where $R_r = (1-m)\rho_r C_r + m\rho_o C_o$ — effective coefficient of thermal content of the soaked porous rock (kJ/kgK).

Solution for the equation (3) under the initial condition of $T(0) = T_s$ is

$$T = T_0 + (T_s - T_0)e^{-\frac{\alpha}{R_r h}t} \quad (4)$$

with $t > t_2^*$.

Differential equation to calculate the condensation front is [9]:

$$\frac{dr_s}{dt} = -\frac{\alpha \Delta T}{l \rho_n m h \overline{\chi}} r_s \tag{5}$$

where m is porosity, $\overline{\chi}$ is volume-averaged value for dryness of steam, ρ_n—oil density (kg/m^3).

At the second stage of CSS we calculate the radius of the condensation front r_k by solving the equation (5) under the initial condition of $r_s(0)=r_k$ as

$$r_k = r_s e^{-\frac{\alpha \Delta T}{l \rho_n m h \overline{\chi}} t}. \tag{6}$$

As a result of soaking the heated oil zone area is ($r_k \le r \le r_*$). If soaking stops before the condensation front reaches the well ($r_k < r_w$), the internal radius of the heated oil zone, i.e. r_k and the external radius of this zone r_* are found as the following balance of heat correlation:

$$R_t h \Delta T \pi (r_s^2 - r_*^2) = R_o h \Delta T \pi (r_*^2 - r_k^2), \tag{7}$$

where $R_o = m \rho_o C_o$ — oil thermal content coefficient (kJ/m^3·K),

$R_t = (1-m)\rho_r C_r$ — effective coefficient of rock thermal content (kJ/m^3·K).

The equation (7) becomes

$$r_*^2 = \frac{R_t r_s^2 + R_o r_k^2}{R_t + R_o}. \tag{8}$$

If we assume that at the beginning of the production stage the internal heated-oil radius instantly becomes r_w. while the external radius — r_{**}. The external radius of this zone, provided that the areas of heated oil at the end of soaking and at the beginning of oil production, is then

$$(r_*^2 - r_k^2) = (r_{**}^2 - r_w^2), \quad r_w^2 \le r_k^2 \le r_s^2 \tag{9}$$

which becomes

$$r_{**}^2 = r_w^2 + (r_*^2 - r_k^2) = r_*^2 - (r_k^2 - r_w^2), \tag{10}$$

or

$$r_{**}^2 = \frac{R_t r_s^2 + R_o r_k^2}{R_t + R_o} - (r_k^2 - r_w^2) < r_*^2. \tag{11}$$

When the condensation front reaches the well, the duration of soaking is determined by the formula

$$t_2^* = \frac{l_g \rho_n m h \overline{\chi}}{\alpha \Delta T} ln\left(\frac{1}{r_s} - \frac{1}{r_K}\right). \tag{12}$$

At the third (oil production) stage of CSS the radius of the hot oil area, which developed during soaking as the oil fluxes moved towards the well, is determined by the formula

$$r_{**}(t) = \sqrt{r_{**}^2 - \frac{Q(r_{**}) R_o t}{\pi h m R_r}}. \tag{13}$$

As viscosity of the filtered fluid depends on the temperature, different temperature zones will contain oil with different viscosity values. The fluid inflow for the well can be calculated by the Dupuit Equation, which is adjusted to account for zones with temperature differences [7]:

$$Q(r_{**}) = 2\pi kh\Delta p\left(\frac{1}{\mu_T \ln\left(\frac{r_{**}}{r_W}\right)+\mu \ln\left(\frac{r_C}{r_{**}}\right)}\right), \tag{14}$$

where μ_T is the viscosity of oil in the bottom-hole zone, heated to the temperature of T, where T is calculated as (4); r_c is the radius of the well's external boundary; Δp is the difference in pressure at the boundary and at the bottom-hole zone.

At the third stage, when the oil is produced, the heated zone shrinks and the radius of the area containing hot oil reaches the time-value of t_3. The equation to define the oil production duration is

$$t_3 = \frac{\pi hmR_r}{Q(r_w)R_o}(r_{**}^2 - r_w^2),\ Q(r_w) = 2\pi kh\Delta p\frac{1}{\mu \ln\left(\frac{r_C}{r_W}\right)}. \tag{15}$$

Thus, the calculations based on the analytical model offered in this research help to estimate the optimal duration of the three stages of CSS for a vertical well: duration of injection, with the account for the changes in steam concentration in the heat conductor as in [10], and for the changes in the hot condensation zone as in [8]. This allows to determine the value of the acquired oil production rate for one steam stimulation cycle and to find the optimal duration of steam injection, soaking and oil production.

The research is based on the following initial data: layer thickness—20 m, porosity—0.34, permeability—1000 mD, temperature—304 K. The layer contained oil with viscosity of 307 mPa and density of 920 kg/m^3, mineral density—2500 kg/m^3, latent heat of evaporation—1025 kJ/kg. The dryness fraction of the injected steam is 0.746 and the temperature is 613 K. One steam stimulation cycle is 108 days. The duration of injection varied from 0 to 60 days, and the duration of soaking—from 0 to 14 days.

Figure 1 shows the isograms of maximum values of NPV for different durations of injection and soaking, as well as the influence curve for correlation between the duration of soaking and duration of injection measured at the moment when the condensation front reaches the well.

Figure 1 shows that of all possible values for injection and soaking durations the maximum NPV of 83,634 roubles is achieved when the duration of injection is 25 days, the duration of soaking is 4 days and the duration of production is 79 days. Figure 1 shows the maximum NPV of 72,197 roubles when the condensation front has reached the well at the injection duration of 24 days, at the soaking duration of 6.5 days and production duration of 77.5 days.

In our earlier research [11] we determined the optimal durations for injection, soaking and production when soaking time depends on the injection time, and the maximum NPV was found on the curve (Fig.1). In this research injection and soak times are variable parameters. It helps to find optimal parameters with higher NPV.

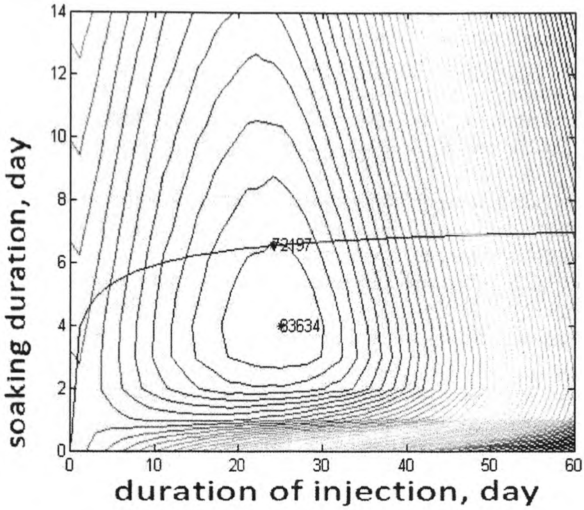

Fig. 1. Different net present values (NPV) at varying durations of injection and soaking and the influence curve of soaking duration as dependant on injection stage length, provided that the condensation front has reached the well

The mathematical model of CSS for bottom-hole zone of a vertical well, described in this research, helps to estimate the economic efficiency of this method at a heavy-oil field.

This paper offers a way to estimate the optimal soaking and production times during CSS of a well. The research results help to determine the maximum NPV for each steam stimulation cycle and find the optimal injection, soaking and oil production times. This model allows to vary soak time taking into consideration the heat in the layer in case when the condensation front has not reached the well. The model can also account for the layer cooling, when the soaking is not over yet, while the condensation front has reached the well.

REFERENCES

1. Iskrickaja, N.I. VNIGRI innovational economic efficiency in heavy oils and natural bitumen field development. *Neftegazovaja geologija. Teorija i praktika — Oil and gas geology. Theory and practice.* 2006. (in Russian).

2. Kudinov, V.I., Savel'ev, V.A., Golovina, T.I. Economic efficiency in thermal methods of oil recovery in «Udmurtneft» oil fields. *«Geologija nefti i gaza» — «Oil and gas geology».* 1998. № 5. (in Russian).

3. Petrov, N.A. *Obosnovanie optimal'nyh parametrov termicheskogo vozdejstvija na zalezhi vysokovjazkih neftej* (diss. kand.) [Grounds for optimum parameters of heat impact on heavy oil reservoirs (Cand. Diss.)]. Uhta, 2009. (in Russian).

4. Kovcek, A.R., Castanier, L.M.. Heavy and Thermal Oil Recovery Production Mechanisms. Standford, 2003.

5. Liu Huiqing, Zhang Hongling and Wang Peixi. Interpretation of temperature profiles during soak period in steam simulated wells. *Petroleum science.* 2007. Vol. 4. №. 4.

6. Ursegov, S.O. *Obosnovanie optimal'nyh parametrov termicheskih tehnologij razrabotki krupnyh mestorozhdenij vysokovjazkih neftej timano-pechorskoj neftegazonosnoj provincii* (diss. kand.) [Grounds for optimum parameters of thermal methods in large heavy oil fields development in the Timan and Pechora oil and gas region (Cand. Diss.)]. Ukhta, 2007. (in Russian).

7. Shevelev, A.P. *Matematicheskoe modelirovanie ciklicheskogo teplovogo vozdejstvija na neftjanye plasty* (diss. kand.) [Mathematical simulation for cyclic heat impact on oil reservoirs (Cand. Diss.). Tyumen, 2005. (in Russian).

8. Chuprov, I.F. *Teoreticheskie i tehnologicheskie osnovy teplovogo vozdejstvija na zalezhi anomal'no vjazkih neftej i bitumov* (diss. doc.) [Theoretical and technological fundamentals for heat impact on extra heavy oils and bitumen reservoirs (Doc. Diss.)]. Ukhna, 2009. (in Russian).

9. Aziz, Kh., Gontijo, J.E. A Simple Analytical Model for Simulating Heavy oil Recovery by Cyclic Steam in Pressure-Depleted Reservoirs. // *paper SPE 13037 presented at the 59th Annual Technical Conference and Exhibition.* Houston. (September 16-19, 1984).

10. Malofeev, G.E. On oil influx mechanism in steam and heat impact on wells. *.Neftjanoe hozjajstvo — Oil Industry.* 1986. № 6. Pp. 38-40. (in Russian).

11. Sokoljuk, L.N., Filimonova, L.N. Calculation of optimum technical parameters in cyclic steam impact on reservoirs. *Neft' i gaz — Oil and Gas.* Tyumen, 2013. № 3. Pp. 61-66. (in Russian).

12.