

Area of Reservoir Heating during Steam Cyclic Treatment of Oil Wells

O V Filimonov, I F Galiullina

Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation

E-mail: Oleg1543@mail.ru

Abstract. To develop difficult-to-recover high-viscosity oils, thermal well treatment methods are applied ensuring the reduction of oil viscosity and the increase of oil recovery, thus decreasing the time of development. Among such methods is steam cyclic well treatment. Steam cyclic method of treatment involves three consecutive stages forming a cycle that can be repeated many times: steam injection stage, steam treatment stage, and oil production stage. The displacement of fluid from reservoir by steam occurs in three stages. The first stage is the formation of the area of the so-called “steam plateau”, which is the region of saturated vapor and water filtration at saturation temperature and reservoir pressure. In this case, the condensation of steam with the heat release takes place, which is sent to reservoir, increasing the temperature in it. The second stage is the displacement of the liquid from reservoir by hot water formed as a result of steam condensation. In the third stage of heat treatment, a stationary temperature field in the reservoir is formed. The whole process of steam cycling is affected by several factors, while the area of reservoir heating is difficult to determine. The integral method proposed in this paper makes it possible to make a preliminary assessment of the heating area of oil reservoir.

1. Introduction

In modern oil production, flowing wells are very rare. There used to be the time when it was just enough to drill a well for the oil to be lifted to the well head. However, in due course, the oil-bearing horizons dried up, the reservoir pressure decreased, the viscosity increased, and as a result oil could no longer flow up spontaneously.

All factors mentioned above facilitated the development of different ways of extracting hydrocarbons, as well as the improvement of machines and equipment for their extraction. At present, a large number of oil production technologies have been developed, which makes it possible to achieve profitable rates of production. Nowadays, scientists and oil engineers have developed a number of more intensive methods of oil production, which are widely used in modern production fields. The main preference is given to thermal and gas methods. Thermal action reduces the viscosity of oil, which leads to an increase in its mobility. The coefficient of thermal expansion of rocks (for quartz) on the average amounts to $\approx 0,38 \cdot 10^{-4}$ 1/degree, oil $\approx 0,95 \cdot 10^{-3}$ 1/°C, water $\approx 0,21 \cdot 10^{-3}$ 1/°C. Thermal expansion of oil-saturated rocks leads to a certain increase in their pore volume, thermal expansion of reservoir fluids also leads to an increase in their volume, however, 10 times greater than in rocks. This factor helps to “squeeze out” some oil from the reservoir. However, thermal



methods require considerable energy inputs, which raises the question of their profitability. Therefore, before giving any recommendation on the technological process to increase oil recovery, careful calculations confirming the economic benefit are carried out [1, 2, 3].

2. Methods and material

The results obtained in the article are based on the analysis of literature data, as well as experimental and analytical methods.

3. Method description and its evaluation

An effective thermal method that intensifies the extraction of viscous oils is steam cyclic treatment of the bottom-hole area. The steam cyclic treatment may positively affect the oil reservoir, as well as reduce the viscosity of the produced fluid, thereby, increasing its flow state [4]. Among the main advantages of steam cyclic treatment are as follows:

- 1) acceleration of the process of propagation and interaction of the coolant with the reservoir;
- 2) increase in the reservoir volume subjected to thermal action;
- 3) capital investments in the development of the field are reduced due to the possibility of reducing the number of injection wells.

Saturated water vapor as a coolant has a very important property, meaning that its temperature at a given pressure remains unchanged until the entire vapor phase condenses. Only after that, the temperature of condensed steam begins to drop (like hot water). The quality of saturated steam is characterized by the degree of its dryness (χ), i.e. the ratio (by weight) of vapor phase to the total mass of wet steam. Commercial steam generators, as a rule, produce steam with dryness $\chi = 0.8$. This steam contains 80% of the vapor phase and 20% of the liquid phase (hot water). The steam dryness is usually determined by operating conditions of steam generators.

When the vapor condenses, its volume decreases sharply, which worsens its oil-displacing properties. To eliminate this drawback, noncondensant gases are added to the steam to produce a more efficient working agent, which is a vapor gas. Combination of water vapor with non-condensable gases (carbon dioxide CO₂, nitrogen N₂ or flue gases) increases the efficiency of oil displacement from the reservoir. Carbon dioxide is highly soluble in oil, besides, it reduces its viscosity, and causes some oil swelling (i.e., increases the amount of oil). To produce a “foamed” vapor, heat resistant surface-active agents are added to it, retaining their foaming properties at the temperature of the injected steam. Its viscosity increases the foaming of steam, contributes to the increase in reservoir coverage by the agent, ensures a more uniform displacement of oil and prevents early steam breakthroughs into the production wells.

The steam cycling treatment involves three successive stages represented in Fig. 1, forming a cycle that can be repeated many times [5, 6]:

1. The stage of steam injection. At this stage the steam is injected into the bottom-hole area and the temperature of the oil reservoir, the oil and all components of the bottom-hole area increases (Fig. 1, a).
2. The stage of steam processing. At this stage the well is closed. The thermal energy passes into the reservoir, the vapor condenses, giving its heat to the collector and reservoir fluids that are in the processing area (Fig. 1, b).
3. The stage of oil production. After the steam processing, the well is put into operation to the marginal cost-effective production rate (Figure 1, c).

Based on the results of steam cyclic treatment of a bottom-hole or of a multihole well, the volume of the produced fluid, as a rule, increases.

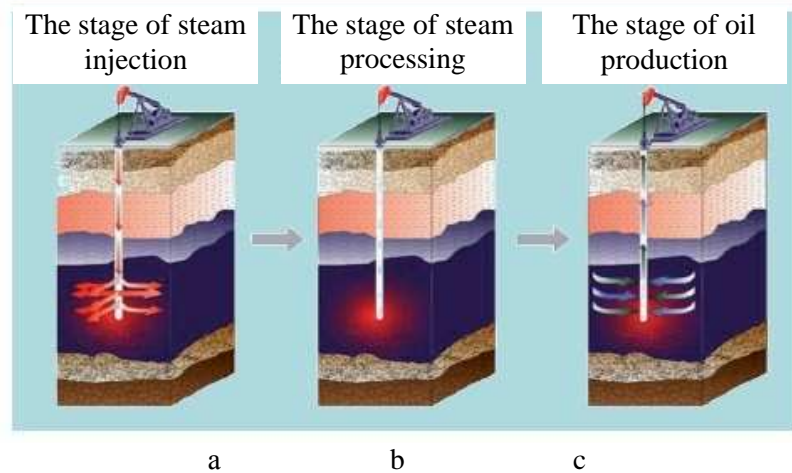


Figure 1. Stages of steam cyclic treatment of the reservoir

In order to assess the quality of steam cyclic treatment, an integral approach is proposed that takes into account the total heat balance of coolant flows introduced into the well in the form of wet steam and transported through the reservoir as saturated water vapor and hot water into surrounding rocks, taking into account the latent heat of steam condensate.

The displacement of reservoir fluid by steam occurs in three stages [7, 8].

The first stage is the formation of area of the so-called “steam plateau”, which is the region of saturated vapor and water filtration at the saturation temperature and reservoir pressure. In this case, the condensation of steam with heat release is observed. The heat is given to the reservoir, increasing its temperature.

As a rule, the wet saturated steam is used the dryness of which is 0.3-0.8. The higher the degree of steam dryness, the more heat content it has in comparison with hot water. So, for example, in wet steam with a degree of dryness of 0.6 at a pressure of 10 MPa and a temperature of 309°C, the heat content is almost 1.6 times greater than that of hot water.

The second stage is the displacement of reservoir fluid by hot water formed as a result of steam condensation. The water released during the condensation of steam acquires the initial temperature of reservoir and is filtered before the condensation front. Condensed water collects some of the heat released during the condensation and when sufficiently large amount of it becomes available, the condensation front stops; however, the reservoir fluid is displaced by hot condensate and steam behind the stationary condensation front. Due to the relatively large coefficient of heat transfer of water and the increasing volume area of its front propagation along the reservoir, the heat losses increase and the hot water temperature drops down rather quickly.

At the third, final stage of heat treatment, a stationary temperature field in the reservoir is formed. The heat loss becomes equal to the amount entering the reservoir and the heat transfer does not occur. Thus, the additional injection of steam no longer leads to an expansion of the heating area.

The structure of thermal field for steam injection is shown in Fig. 2, where r_s is the current coordinate of steam-gas front; r_f is the radius of the area of maximum heating of bottom-hole area; T_0 is the initial temperature of reservoir; T_s is the vapor saturation temperature; r_w is the well radius; t is the injection time of steam.

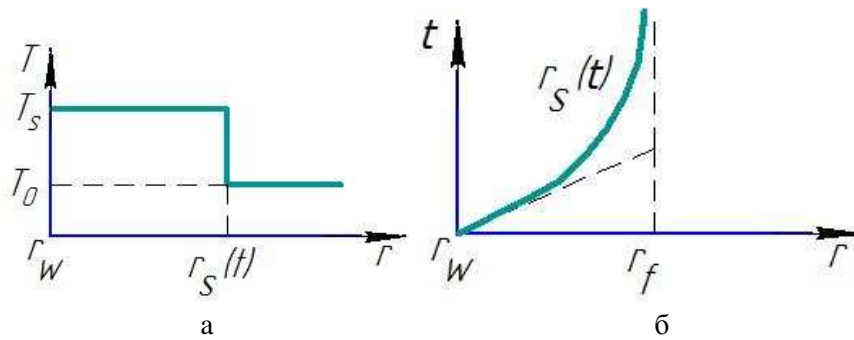


Figure 2. Diagram of thermal field structure when injecting steam into oil reservoir:

a - stepwise form of temperature distribution within the bottom-hole area; b - propagation path of thermal front (solid curve) and an approximation accepted in the proposed integral approximation (dotted curve).

First, it is necessary to determine how much heat enters the reservoir at a constant steam injection rate; the heat input rate is calculated by the following formula:

$$H = mc(t_2 - t_1) = q_n \rho_g [c_w (T_s - T) + l_g] \quad (1)$$

where H is the rate of heat injection into the reservoir (kJ/day);

q_n is the speed of steam injection (m^3/day);

ρ_g is the steam density (kg/m^3);

c_w is the heat capacity of steam (kJ/kgK);

T_s is the steam saturation temperature in reservoir conditions (K);

T_0 is the reservoir temperature;

l_g is the latent heat of vaporization (kJ/kg).

Let us assume that the thermal losses obey the Newton-Richman law presented in the following equation:

$$q = \alpha \cdot (T_s - T_0) = \alpha \cdot \Delta T, \quad (2)$$

where q is the specific heat loss from porous medium to the roof and the base of reservoir (W/m^2);

α is the heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$);

T_s is the saturation temperature (K);

T_0 is the reservoir temperature (K).

Understanding the structure of thermal field and taking into account that the thermal saturation of reservoir is determined by its temperature and heat capacity, it is possible to calculate the total heat losses from the heated area to the roof and the base of reservoir using the following formula:

$$W = \int_{r_w}^{r_f} 2\pi r \alpha \Delta T dr = \pi \alpha \Delta T (r_f^2 - r_w^2), \quad (3)$$

where W is the heat loss in the roof and the bottom of reservoir (W);

r_f is the radius of the heated area (m);

r_w is the radius of the well (m).

In the area of a steam plateau, the formation temperature is equal to the saturation temperature $T(r_s) = T_s$. Taking these data into account the integral in formula (3) can be solved analytically.

By equating two formulas (1) and (3) one may find the maximum radius of reservoir heating [5, 6, 12]:

$$r_f = \left[\frac{q_n \rho_g (c_w \Delta T + l_g)}{\pi i \Delta T} + r_w^2 \right]^{1/2}, \quad (4)$$

The experience of applying this method is economically viable in the following cases [9]:

- 1) reservoir depth is not more than 900-1,200 m;
- 2) collector capacity is not less than 15 m;
- 3) oil viscosity in reservoir conditions is higher than 200 cP;
- 4) residual oil saturation of reservoir before steam-heat treatment is not less than 50%;
- 5) oil density under reservoir conditions is not less than 0.9-0.93 t/m³.

4. Conclusions

As a result of steam cycling treatment it is possible to determine the radius of heating of the oil reservoir. However, this method takes into account the minimum number of factors affecting the final result. It can be used only for a preliminary assessment of the area of oil reservoir heating. For a more accurate assessment an individual approach to each treated well located at a particular field is required [10, 11]. Before steam injection, it is necessary to give a complete characterization of the well, namely: to determine its operational parameters (oil, water, gas factor and others) and to carry out a complex of geological and research works to measure reservoir pressure, temperature, static level, etc.

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