Effect of bottom water on performance of cyclic superheated steam stimulation using a horizontal well

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Abstract

Horizontal well has been widely used for heavy-oil recovery in the petroleum industry. Besides, superheated steam has been proved effective in heavy-oil recovery by field practice. In this paper, a numerical model is established with the help of numerical simulator. The effect of bottom water on the productivity of cyclic superheated steam stimulation well has been studied. Some interesting findings show that: (a) the bottom water-channeling phenomenon becomes more severe when the horizontal well is approaching the bottom water. (b) The cyclic oil production fluctuates with periodic number when the horizontal well is close to the bottom water due to the fact that the injected water has an elastic push action on the bottom water. (c) A larger-bottom water size is able to supply a larger elastic energy. While the cyclic oil production of large-bottom water size for the first few cycles is smaller than that with a small-bottom water, it may be turned over for the last few cycles.

Keywords Heavy oil · Horizontal well · Cyclic superheated steam stimulation · Bottom water · Size of water body · Numerical analysis

Introduction

Horizontal wells have been widely used for heavy-oil recovery, as well as geothermal energy development (Fengrui et al. 2017a, b, Fengrui et al. 2018a, b, c). In the heavy-oil industry, horizontal wells are always selected for the steam-assisted gravity drainage process, steam flooding, as well as the cyclic steam stimulation process (Fengrui et al. 2018d, e, f, g, h, i, j, k, l, 2019a; Ganesh et al. 2019; Zargar and Ali 2018; Baghernezhad et al. 2019; Venkatramani and Okuno 2018; Bao et al. 2016). This is because, compared with the

vertical well, horizontal well processes the multi-advantages of a larger contact area with oil reservoir, a higher production rate as well as a larger well-controlled volume (Khan and Awotunde 2018; Muradov and Davies 2012).

On the other hand, the selection of thermal fluid is an important task in the thermal industry (Fengrui et al. 2017c, d, e, f, g). From the physical aspect of view, it is always focused on the mass and heat transfer characteristics of thermal fluid in the study system (Fengrui et al. 2018m, n, o).

In recent years, superheated steam (Fengrui et al. 2018p, q, r, 2019b), supercritical CO₂ and multi-component thermal fluid (Haitang et al. 2019; Fengrui et al. 2017h, 2018s, t, u, v, 2019c, h) were widely adopted in thermal recovery of heavy oil as well as in geothermal energy recovery (Fengrui et al. 2018w, x, 2019c, d, e, f, g). In this paper, superheated steam is selected as the study object. A model of cyclic superheated steam stimulation in a bottom-water heavy-oil reservoir is established with the numerical simulator. Then, the effect of bottom water on the performance of cyclic superheated steam stimulation well has been studied.

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Table 1 Reservoir and operation parameters of the numerical model

Physical parameter	Value	Physical parameter	Value
Reservoir size (m)	450×200×20	Superheated steam temperature (°C)	316
Grid size (m)	10×10×2	Soak time (day)	10
Buried depth (m)	300	Injection pressure (kPa)	5000
Porosity, dimensionless	35.6	Length of the horizontal well (m)	250
Rock compression coefficient (kPa ⁻¹)	3.65×10^{-5}	Reservoir temperature (°C)	13.5

Fig. 1 Oil viscosity vs. temperature

The numerical model

With the help of numerical simulator, a model is built for the cyclic superheated steam stimulation well with a bottom water body. The reservoir thickness is 20 m. The permeability in the I direction is 1000 mD. The distance of horizontal well to bottom water is 12 m. The oil saturation is 0.79. The viscosity of oil under reservoir condition is 8500 mPa s. The ratio of vertical permeability to horizontal permeability is 0.3. The superheated degree is 30 K. The periodic steam injection is 2000 t. The other parameters are shown in Table 1.

The viscosity of heavy oil against temperature is shown in Fig. 1. It is observed that the viscosity of heavy oil is close to zero when the temperature is higher than 50 °C.

The relative permeability curve adopted in this paper is shown in Fig. 2. Figure 2a shows the oil and water relative permeability, while Fig. 2b shows the gas and liquid relative permeability.

The 3D view and the I–J view of the numerical model is shown in Fig. 3. The half above is the oil reservoir, while the below half is the bottom water. Note that the capillary force is neglected in this paper so that there is a clear boundary between oil and bottom water.

Fig. 2 The relative permeability adopted in the numerical simulation

Results and discussion

In oil field, one of the key issues is to determine the distance from horizontal well to bottom water. In this part, the effect of distance from horizontal well to bottom water on performance of cyclic superheated steam stimulation wells has been revealed. The distances are selected as 4 m, 8 m, 12 m, 16 m. The simulated results are shown in Figs. 4 and 5.

Figure 4 shows the macroscopic law of the effect of distance from horizontal well to bottom water on final recovery degree. It is observed that the final recovery degree increases with increase of the distance. This is because the bottom water-channelling phenomenon becomes more severe when

Fig. 3 The sketch map for the numerical model

Fig. 4 Effect of distance from horizontal well to bottom water on final recovery degree

the horizontal well is approaching the bottom water. The curves shown in Fig. 4 are the accumulative values of the cyclic oil production rate. A further view is shown in Fig. 5 to reveal the cyclic performance.

Figure 5 shows the effect of distance from horizontal well to bottom water on cyclic oil production. It is observed that: (a) the cyclic oil production decreases with periodic number. This is because the oil saturation and reservoir pressure decrease with periodic number. (b) Another interesting phenomenon is that the cyclic oil production fluctuates with periodic number when the horizontal well is close to the bottom water. For instance, the cyclic oil production for the sixth cycle is smaller than both the fifth cycle and the seventh cycle. This is because

Fig. 5 Effect of distance from horizontal well to bottom water on cyclic oil production

the injected water has an elastic push action on the bottom water, which is shown in Fig. 6.

Figure 6 shows the water saturation at heel-point of the horizontal well at the end of soak period of the sixth and seventh cycle. It is observed that the bottom water has been pushed back to a lower position after the superheated steam has been injected into the reservoir in the seventh cycle. Consequently, the water saturation near the heel-point of wellbore has been decreased. This is the main reason why the productivity of the following cycle may be higher than its previous cycle, as shown in Fig. 5.

However, the cyclic oil production rate always decreases with periodic number when the horizontal well is far from the bottom water. It is observed from Fig. 7 that: (a) the bottom water reaches the wellbore at the end of the first cycle. The water saturation near the wellbore increases with periodic number. (b) The bottom water is hard to reach when the wellbore distance is equal to 12 m. As a result, the thermal well should be located at the upper part of the reservoir to prevent the bottom water-coning phenomenon from happening too early.

Another issue is studied to reveal the effect of bottom water body size on the oil productivity rate. The simulated results are shown in Figure 8 where the effect of bottom water body size on the recovery degree can be seen. It is observed that the recovery degree has been greatly decreased when there is a bottom water body. What's more, the recovery degree decreases with bottom water size. However, a larger bottom water size is able to supply a larger elastic energy, as shown in Fig. 9. It is observed from Fig. 9 that the cyclic oil production decreases with periodic number when the bottom water size is at a small level. However, when the bottom water size is 20 times of reservoir, the cyclic oil production decreases slowly with periodic number. Besides, while the cyclic oil production of large bottom water size for the first few cycles is smaller than that with

Fig. 6 Interpretation for the fluctuation phenomenon of cyclic oil production when the horizontal well is close to the bottom

Fig. 7 Bottom water-coning phenomenon under different distance from horizontal well to bottom water condition

Fig. 8 Effect of bottom water body size on the recovery degree

Fig. 9 Effect of bottom water body size on the cyclic oil production

a small bottom water, it may be turned over for the last few cycles. This is because the large bottom water possesses a larger elastic energy which can be used for oil production when the reservoir pressure has been greatly decreased for the last few cycles.

For further learning on superheated steam injection for heavy-oil recovery, the following articles are recommended (Xu et al. 2013; Chen et al. 2018; Kondoh et al. 2016; Aju-mobi et al. 2018; Fan et al. 2016; Liu et al. 2018).

Conclusion

In this paper, a numerical model is established with the help of numerical simulator. The effect of bottom water on the productivity of cyclic superheated steam stimulation well has been studied. Some interesting findings are shown below.

- The bottom water-channeling phenomenon becomes more severe when the horizontal well is approaching the bottom water.

- (b) The cyclic oil production fluctuates with periodic number when the horizontal well is close to the bottom water due to the fact that the injected water has an elastic push action on the bottom water.
- (c) A larger bottom water size is able to supply a larger elastic energy. While the cyclic oil production of large bottom water size for the first few cycles is smaller than that with a small bottom water, it may be turned over for the last few cycles.

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