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A New Analytical Model of Productivity Prediction for Offshore Heavy Oil Reservoir With Cycle Steam Stimulation by Horizontal Wells

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Abstract
The heavy oil thermal recovery technology has been widely used in land oil field both at home and abroad, but no precedent of offshore thermal recovery (except beach) was reported so far because of the platform limitation and operating cost restriction. Offshore thermal recovery needs higher oil recovery rate and higher cumulative oil production of each well. As for an offshore heavy oil reservoir, which can produce oil by natural energy of formation, the ratio of thermal productivity and cold productivity (oil productivity increment factor) decides whether development by thermal recovery or not. Due to the huge investment of offshore oil field development, too high or too low productivity evaluation will have serious consequences for oilfield exploration and development, so it is very important to make reasonable prediction of the relative oil productivity index (ROPI). Due to the complexity, there is no prediction model of ROPI for horizontal well CSS. Based on horizontal well productivity formula for cold production, on the basis of heated radius of CSS horizontal well, combining with the viscosity-temperature curve of heavy oil, considering the viscosity changes with temperature in heated area, a new analytical model of CSS horizontal well productivity prediction is derived. By the new model, it is easy to get the ROPI of CSS. The research results show that thermal recovery ROPI mainly influenced by heated radius, reservoir thickness and horizontal section length. Case study of CSS horizontal well in N heavy oil field in Bohai shows that, the average oil productivity of first injection cycle is 1.5 ~ 1.6 times of that of cold production, and it is in accordance with that of the prediction model. The new analytical model fills the gap between the complex numerical simulation method and simple experience method, which is of great significance for designing reservoir project of offshore heavy oil.

Key words: Heavy oil; Horizontal well; Cycle steam stimulation; Productivity prediction; Analytical model

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INTRODUCTION
Heavy oil, one of the most important petroleum resources, is widely distributed in many countries, especially in Canada, Venezuela, USA, China, and so on[1]. However, because of the high viscosity of the heavy oil, the natural flow of heavy or viscous oils does not easily occur in the reservoir[2-3]. Application of steam injection technology to heavy oil reservoirs is the most commercially successful EOR method[4-7]. Nowadays, CSS, a steam injection method, is known as the most widely used and mature technology, recently introduced for offshore heavy oil recovery[8]. A variation on this recovery process is to co-inject N_2 and CO_2 with steam[9].

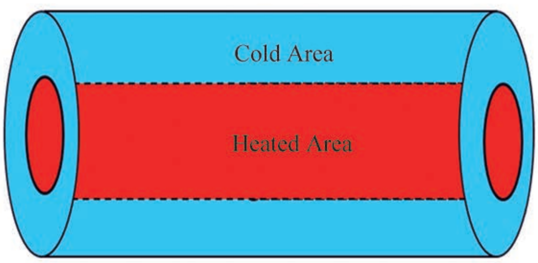
In recent years, the Bohai oilfield in China found a number of heavy oil field. From the present performance and forecast indicators of pilot test, heavy oil of viscosity lower 350 mPa·s in formation conditions, can be developed high-efficiency. It has the oil productivity of 40 m^3/d and 15% predicted oil recovery by natural energy development. But for the oil viscosity higher 350 mPa·s, is poor economic benefit due to lower oil productivity and lower oil prediction recovery by cold production. In order to improve the offshore unconventional heavy oil (higher 350 mPa·s) development effect, pilot test of thermal recovery by horizontal well CSS was carried out in offshore heavy oilfield. As for an offshore heavy oil reservoir, which can produce oil by natural energy of formation, the ratio of thermal productivity and cold productivity (oil productivity increment factor) decides whether development by thermal recovery or not. Due to the huge investment of offshore oil field development, too high or too low productivity evaluation will have serious consequences for oilfield exploration and development, so it is very important to make reasonable prediction of the relative oil productivity index of CSS horizontal well (ROPI).

The current evaluation methods of oil productivity, such as logging, seismic, well test and wire line formation testing and so on, cannot meet the needs of the thermal recovery at present. Oil productivity of cold production can be determined by DST testing, and then oil productivity of thermal recovery can be obtained by multiple the ROPI. The productivity increment ratio of thermal recovery is an important parameter, the higher its value, the better effect of thermal recovery. For heavy oil, cold productivity can be sometimes obtained by testing, but ROPI can't be accurately determined.

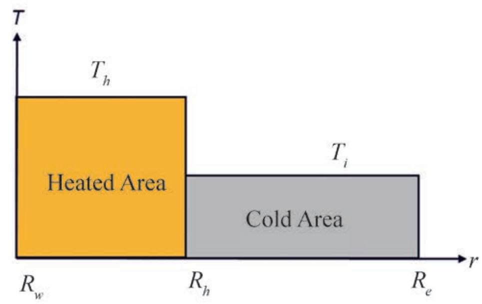
As for horizontal well productivity of cold production, a lot of formulas were deduced and reported[10-11]. About thermal recovery horizontal well productivity, fewer scholars have studied. Hong-ling Zhang deduced the calculation model of reservoir pressure at the interface between cold and heated. Its shortcoming is using the simple average method to calculate the heat volume[12]. Zhang established a flow dynamic model of the coupling the non-isothermal temperature within the reservoir seepage flow and metamorphic quantity pipe flow in horizontal wellbore[13]. But the heated radius of horizontal well was calculated in the literature by the vertical wells heating theory. Wang also established an analytical model of horizontal well productivity, but the formula is too complicated, and lack of the influence analysis of key parameters on the oil productivity[14]. So based on conventional horizontal well productivity formula, a simple and practical analytical model of CSS horizontal well oil productivity is derived.

1. CONCEPTUAL MODEL AND ASSUMPTIONS

After steam injection, seepage area can be divided into two areas, such as hot area and cold area, which is shown in Figure 1(a). Suppose hot area is isothermal region, and the temperature is the average formation temperature after soaking. The temperature of cold zone is the initial formation temperature, which is shown in Figure 1(b). Within the heated zone, viscosity of crude oil has greatly reduced with the increase of temperature, as shown in Table 1. Outside the heated zone, temperature and oil viscosity are the initial reservoir temperature and viscosity.



(a) Conceptual Model of CSS Horizontal Well



(b) Temperature Distribution of CSS Horizontal Well

Figure 1
Diagram for the Horizontal Well of Cycle Steam Stimulation

Table 1
Typical Oil Viscosity-Temperature Curve of N Heavy Oil Field

Temperature /℃	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Viscosity /mPa·s	45,412	23,424	13,051	7,565	4,772	2,980	1,951	1,306	879	631	458	333	249	187	152

The mathematical model is subject to the following basic assumptions: a) single phase, and steady-state flow; b) slightly compressible fluid; c) reservoir is isotropic and homogeneous, regardless of the formation damage; d) outer boundary and wellbore pressure are constant; e) seepage area is divided into hot and cold area.

2. DERIVATION OF MATHEMATICAL MODEL

Oil productivity calculation formula of horizontal well by conventional development such as water flooding is usually obtained by the steady flow analytical solution. Steady-state refers to the reservoir which pressure does not change over time at any point. In practice, almost no reservoir develops under steady-state conditions. Nevertheless, the steady-state solution is still widely used[15]. The reasons are as follows: firstly, steady-state solution is easy to get by the analytical method; secondly, steady-state results can be easily converted into non-steady-state results and quasi-steady-state results by extending drain boundary, the effective well bore radius and shape factor concept which changes over time. Based on horizontal well productivity formula for cold production, a new analytical model of CSS horizontal well productivity prediction is derived.

2.1 Horizontal Wells Oil Productivity for Cold Production

When the reservoir is development by cold production, oil involved in the following fluid flow relationship[10]:

$$p_e - p_{wf} = \frac{q_l \mu_l}{2\pi K K_{rol} h}\left[\ln\frac{a_l + \sqrt{a_l^2 - (L/2)^2}}{L/2} + \frac{h}{L}\ln\frac{(h/2)+\delta}{R_w}\right]. \tag{1}$$

Oil productivity index for cold production horizontal well is:

$$J_l = \frac{q_l}{p_e - p_{wf}} = \frac{2\pi K h}{\frac{\mu_l}{K_{rol}} A_l}. \tag{2}$$

Where:

$$A_l = \left[\ln\frac{a_l + \sqrt{a_l^2 - (L/2)^2}}{L/2} + \frac{h}{L}\ln\frac{(h/2)+\delta}{R_w}\right], \tag{3}$$

$$a_l = a_c = \frac{L}{2}\left[0.5 + \sqrt{0.25 + \frac{1}{(0.5L/R_e)^4}}\right]^{0.5} \left(\text{When } L > \beta h, \frac{L}{2} < 0.9R_e\right). \tag{4}$$

2.2 Horizontal Wells Oil Productivity for Cycle Steam Stimulation

When the reservoir has been injected steam, the flow region can be divided into hot and cold zone, which is shown in Figure 2. The hot zone is isothermal zone, and the temperature of hot zone is the average formation temperature T_{avg} at the end of steam soaking while the temperature of cold zone is the original formation temperature T_i.

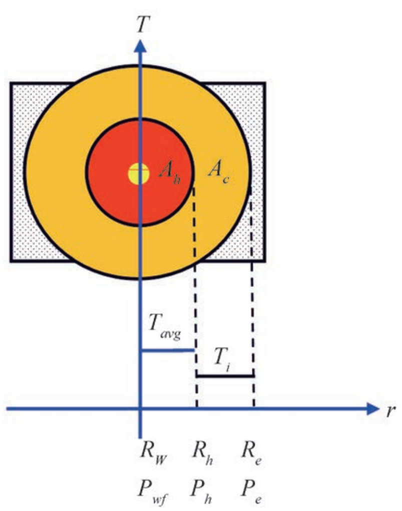


Figure 2
Profile for Hot and Cold Zone After Steam Soaking

With regard to heated zone (inner cylinder):

$$p_h - p_{wf} = \frac{q_h \mu_h}{2\pi K_{ho} h}\left[\ln\frac{a_h + \sqrt{a_h^2 - (L/2)^2}}{L/2} + \frac{h}{L}\ln\frac{(h/2)+\delta}{R_w}\right], \tag{5}$$

$$a_h = \frac{L}{2}\left[0.5 + \sqrt{0.25 + \frac{1}{(0.5L/R_h)^4}}\right]^{0.5} \left(\text{When } L > \beta h, \frac{L}{2} < 0.9R_e\right). \tag{6}$$

As for cold zone (outside the cylinder):

$$p_e - p_h = \frac{q_c \mu_c}{2\pi K_{co} h}\left[\ln\frac{a_c + \sqrt{a_c^2 - (L/2)^2}}{L/2} + \frac{h}{L}\ln\frac{(h/2)+\delta}{R_h}\right], \tag{7}$$

$$a_c = \frac{L}{2}\left[0.5 + \sqrt{0.25 + \frac{1}{(0.5L/R_e)^4}}\right]^{0.5} \left(\text{When } L > \beta h \text{ and } \frac{L}{2} < 0.9R_e\right). \tag{8}$$

According to the principle of continuity of quality, so that:

$$q_h = q_c = q_s. \tag{9}$$

Equations (5) and (7) are added:

$$p_e - p_{wf} = \frac{q_s}{2\pi K h}\left(\frac{\mu_h}{K_{roh}} A_h + \frac{\mu_c}{K_{roc}} A_c\right), \tag{10}$$

$$A_h = \left[\ln \frac{a_h + \sqrt{a_h^2 - (L/2)^2}}{L/2} + \frac{h}{L} \ln \frac{(h/2)+\delta}{R_w} \right], \tag{11}$$

$$A_c = \left[\ln \frac{a_c + \sqrt{a_c^2 - (L/2)^2}}{L/2} + \frac{h}{L} \ln \frac{(h/2)+\delta}{R_h} \right]. \tag{12}$$

Oil productivity index for CSS horizontal well is:

$$J_h = \frac{q_s}{p_e - p_{wf}} = \frac{2\pi K h}{\left(\frac{\mu_h}{K_{roh}} A_h + \frac{\mu_c}{K_{roc}} A_c \right)}. \tag{13}$$

2.3 Oil Productivity Increment Factor for CSS Horizontal Wells

As for heavy oil of lower oil viscosity, which the natural flow can be occur in the reservoir, the oil production rate of natural energy and water flooding is very low. So an important parameter ROPI was defined as the ratio of the oil productivity of CSS to the oil productivity of conventional cold production. Through Equations (2) and (13), it gets:

$$\text{ROPI} = \frac{J_h}{J_l} = \frac{\frac{\mu_l}{K_{rol}} A_l}{\frac{\mu_h}{K_{roh}} A_h + \frac{\mu_c}{K_{roc}} A_c}. \tag{14}$$

If the change of relative permeability of oil is taken no account of, Equation (14) can be represented as:

$$\overline{J} = \frac{J_h}{J_l} = \frac{A_l}{\frac{\mu_h}{\mu_l} A_h + A_c}. \tag{15}$$

At the beginning of production, the heating zone temperature is very high; viscosity of heated crude oil is far less than that of the original condition oil, thus:

$$\frac{\mu_h}{\mu_l} \approx 0. \tag{16}$$

Simplified Equation (15) can get the maximum ROPI:

$$\text{ROPI}_{\max} = \frac{J_h}{J_l} = \frac{A_l}{A_c} = \frac{\ln \frac{a_l + \sqrt{a_l^2 - (L/2)^2}}{L/2} + \frac{h}{L} \ln \frac{(h/2)+\delta}{r_w}}{\ln \frac{a_c + \sqrt{a_c^2 - (L/2)^2}}{L/2} + \frac{h}{L} \ln \frac{(h/2)+\delta}{r_h}}. \tag{17}$$

3. INFLUENCE FACTORS ANALYSIS

By Equation (17), it can be concluded that: the relative oil productivity index of reservoir after heated does not depend on reservoir thickness and permeability, but depending on the scope of heated oil layer and the degree of oil viscosity decreased. A parameter of dimensionless heated radius was defined as the heated radius of CSS to the drainage radius. So, the figures of dimensionless heated radius and oil viscosity in the heated zone influence to the relative oil productivity index can be drawn according to Equations (15) and (17).

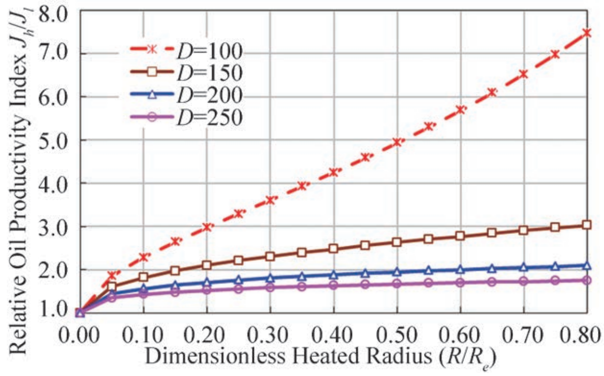


Figure 3
Influence of Dimensionless Heated Radius

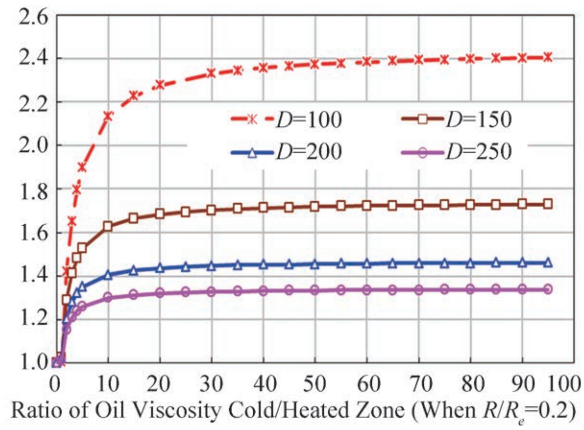


Figure 4
Influence of Oil Viscosity

3.1 Effect of Heated Radius

Figure 3 shows that well spacing has a great influence on ROIP under the condition of the same dimensionless heating radius. According to dimensionless heated radius of 0.1 ~ 0.2, it is clear that the maximum relative oil productivity index of CSS horizontal well is in the range of 1.4 ~ 3.0. So in order to enlarge the heated radius at some well space, more steam and higher temperature, higher steam quality are helpful and needed.

3.2 Effect of Temperature and Oil Viscosity

Figure 4 shows that the oil viscosity ratio of cold zone to heated zone has the limited influence to the relative oil productivity index under the condition of the same dimensionless heating radius. After the oil viscosity of heated zone reduced to crude oil viscosity of the initial formation, the relative oil productivity index gradually tends to stabilize with the ratio (oil viscosity of cold zone divided that of the heated zone) increases. Before the ratio are less than 20, the relative oil productivity index increase rapidly with the increment of the ratio. So, in order to obtain a good relative oil productivity index, higher temperature is helpful and needed, but excessively high temperature is less helpful.

4. FIELD CASE STUDY

The characteristics of N heavy oil field are as follows: fluvial facies sedimentation, average porosity of 35%, average permeability of 4,564×10^{-3} μm^2, complex oil-water relationship, mainly the lithologic-structural oil reservoir, with little edge-bottom water, oil viscosity of 450 ~ 950 mPa·s in formation condition. On the basis of theoretical research in 2010, the Bohai oilfield has built the first thermal recovery pilot test area in China. Currently offshore heavy oil thermal recovery pilot test has been carried out which takes the advantage of a synergistic effect made from N_2 and CO_2 of flue gas with steam. By the end of 2015, there have been 10 wells which completed the first cycle of thermal recovery stimulation.

Table 2
Calculation Parameters of Typical Horizontal Well of N Oil Field

Parameter name	Value	Parameter name	Value
Equivalent hot water injection speed /(m^3/d)	293.5	Formation oil viscosity /mPa·s	630
Hot water heat capacity /kJ/kg	4.2	Formation permeability /mD	3,000
Equivalent hot water injection temperature /℃	240	Well spacing /m	300
Total injection calories /kJ	3.45×10^9	Production pressure drop /Mpa	1.5
Horizontal well length /m	200	Steam injection time /d	18
Reservoir thickness /m	9	Soak time /d	5
Distance of horizontal well to the top/m	4		

This paper selects typical horizontal well thermal parameters as an example, as shown in Table 2, with a method which takes the total enthalpy of multi-thermal fluids as equivalents of the same temperature of the hot water.

In order to verify the mathematical model, the heated radius is calculated according the methods of literature[16], and the results are shown in Figures 5 and 6.

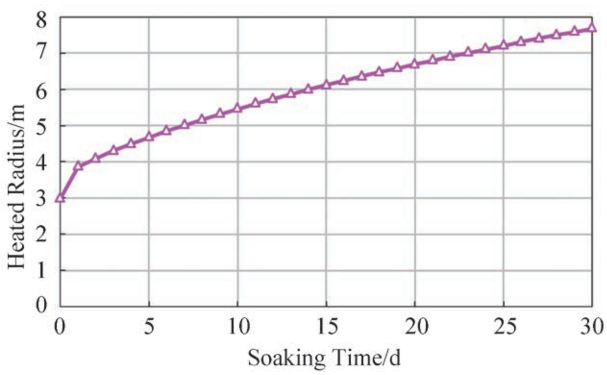


Figure 5
Heated Radius Change With the Soaking Time

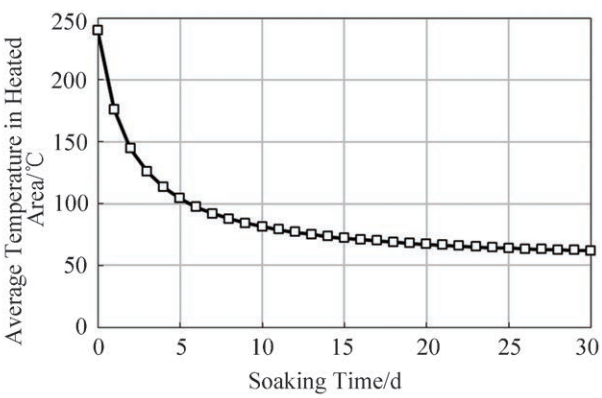


Figure 6
Average Temperature in Heated Area

Also, the commercially available thermal reservoir simulator, STARS, developed by Computer Modeling Group (CMG), is adopted. The basic reservoir and fluids properties, including simulation input parameters, can be obtained from typical horizontal well, as listed in Table 2. In addition, the grid size is 20 × 40 × 20 and the corresponding block dimensions in *I*, *J* and *K* directions are 0.5 m, 5 m and 0.5 m, respectively. And the border is a closed border. Thermal parameters in the model are the same parameters as the theoretical model calculations, temperature field after the end of the soak has shown in Figure 7. The original reservoir temperature of the model is 56 ℃, when the heating temperature is higher than 100 ℃, the display area is showing annulus.

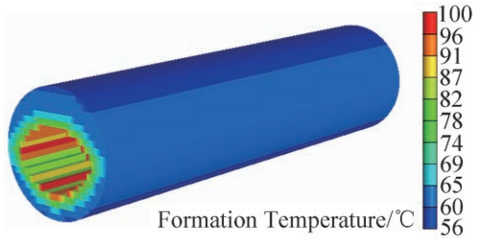


Figure 7
Temperature Field After Steam Injection

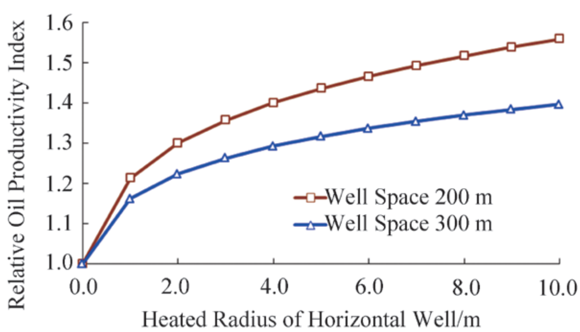


Figure 8
ROPI Calculated by Analytical Model

Calculation of horizontal well in N heavy oil field in Bohai shows that, the heated radius of CSS horizontal well is about 6 ~ 10 m, and the average oil productivity of first injection cycle is 1.5 ~ 1.6 times of that of cold production for well space 200 m, which is shown in Figure 8.

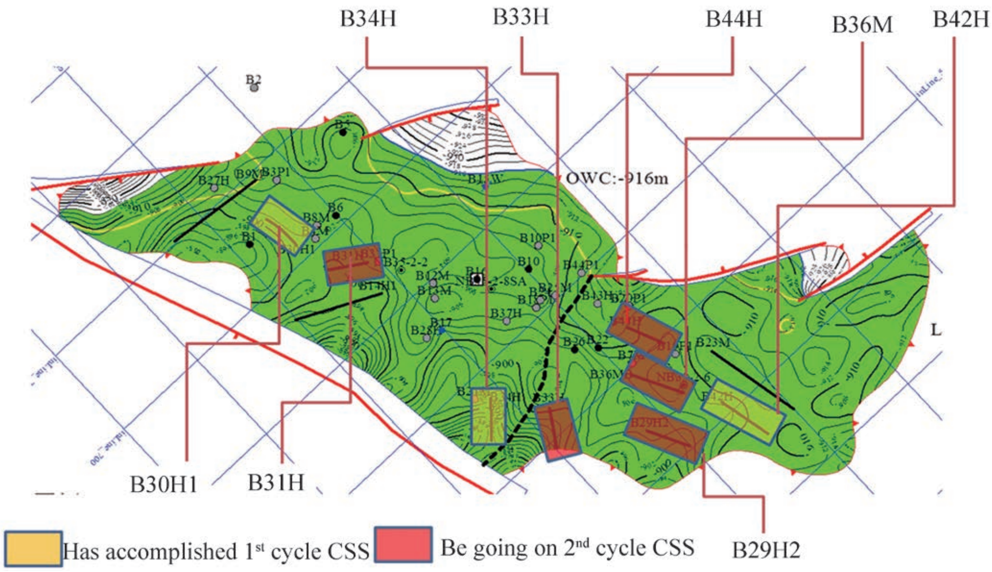


Figure 9
Thermal Wells of N Heavy Oil Field

Table 4
First Cycle of CSS Horizontal Well Oil Productivity Statistics Results of N Heavy Oil Field

Well names	Thermal validity period/d	Cumulative oil production volume in thermal validity period/10^4 m^3	CSS average oil productivity / (m^3/d)	Average productivity of cold production / (m^3/d)	ROPI
B28H	172	0.96	55.7	32	1.7
B43H	120	0.61	50.5	32	1.6
B30H1	248	1.03	41.6	23	1.8
B31H	250	1.21	48.6	32	1.5
B29H2	265	1.29	48.7	28	1.7
B36M	450	2.60	57.8	38	1.5
B42H	245	1.00	40.7	24	1.7
B44H	340	1.37	40.3	24	1.7
B34H	430	2.89	67.3	42	1.6
B33H	445	2.24	50.3	35	1.4
Average value	297	1.52	50.2	31	1.6

Up to now, there are 10 wells finished the first CSS, which is shown in Figure 9. The average injection parameters are as follows: Single well injection volume of hot water in first cycle is about 3,000 ~ 4,700 m³, the average is 3,368 m³, N_2 and CO_2 injection volume is about 25×10^4 ~ 135×10^4 Nm^3 (a standard atmospheric pressure, temperature of 0 ℃, relative humidity is 0% when the volume), the average is 88.8 $\times10^4$, injection temperature is 240 ~ 280 ℃ (ground). In present multi-thermal fluids generator, the volume fraction of N_2 and CO_2 is 88% and 12% respectively. According to the surrounding well analogy research to determine the cold production rate of 24 ~ 42 m³/d, and after injection multi-thermal fluid, the average oil production of first injection cycle is about 40 ~ 67 m³/d, which as shown in Table 4.

Through performance evaluation, the relative oil productivity index of thermal recovery wells of first injection cycle is about 1.4 ~ 1.7 times that of cold production and the average value is 1.6. The results of well on site is accordance with the prediction results from the new analytical model.

CONCLUSION

(a) Based on the research of horizontal well productivity formula for CSS, a new analytical model of CSS horizontal well productivity prediction is derived. By the new model, it is easy to get the relative oil productivity index of CSS, which is very important to make reasonable prediction of thermal recovery design in offshore heavy oilfield.

(b) The relative oil productivity index of CSS depends on the heated scope and decrement of the crude oil viscosity. Under the condition of the same spacing, the ROPI increase with the dimensionless heating radius increases.

(c) An analytical model with clear physical concept and simple engineering calculation can fill the gap between complex numerical simulation method and simple method of experience. The new analytical model can be simple and effective to help on-site.

Nomenclature Symbols

T_i The initial reservoir temperature, ℃
T_{avg} Average temperature in hot area, ℃
R_h Heat radius at the end of steam soaking, m
R_w Well bore radius, m
P_e Drain boundary pressure, MPa
P_{wf} Bottom hole pressure, MPa
q_l Cold region outflow, m^3/d
μ_l Average formation oil viscosity in cold area, MPa·s
K Formation absolute permeability, $10^{-3}\mu m^2$
K_r Cold zone oil relative permeability, fractional
h Reservoir thickness, m
L Horizontal well length, m

Subscripts

o Oil phase
w Water phase
l Cold area
h Hot area

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