The Research of Vapor Phase Front Migration Rules in Steam Assisted Gravity Drainage

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ABSTRACT

The degree of steam overlay and descriptions of the migration rules for vapor front are considered one of the greatest challenges to research the seepage laws of steam assisted gravity drainage. In order to surmount these challenges, the theory of percolation mechanics are introduced, combined with the well group structure of steam assisted gravity drainage, we do workings such as establishing the mathematical model of pressure field, applying the steam overlap theory and simplifying the steam overlap coefficient, adopting the technology of database and mapping to display the trends of vapor front intuitively. At last, combined with production factor and reservoir thickness, we analyze the sweep volume of steam and the influence rules of the vapor front migration. Understanding the achievements will provide scientific basis to the improvement of steam's sweep volume in symmetry elements, displaying the working degree of reservoirs intuitively as well as the efficient development of steam assisted gravity drainage.

1. INTRODUCTION

SAGD technology was first proposed in 1978 and was applied to the development of heavy oil reservoirs after a lot of simulation tests [1]. In1996, pilot tests were carried out in the DU 84 of Liaohe oilfield, having made great progress so far [2]. Owing to the aeolotropism of subaerial deposition reservoirs is serious in China, and adopting the method that injecting steam from vertical wells can adjust the profiles of injection steam flexibly, therefore, the growth of steam chamber have great influence on the development effectiveness of SAGD in the process of SAGD development. The research of vapor phase front's migration can display the growth of steam chamber intuitively [3, 4, 5]. In order to show the working degree of the reservoir and the well's situation intuitively, G. Mandal and C. W. Volek established the frontal displacement model of thermal recovery in 1969, predicting the expansion of steam drive with time, but it didn't consider the phenomenon of steam overlap [6].

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N.A.Myhill and G.L.Stegemeier made the further revision to the model which was established by G.Mandal and C.W.Volek, another frontal displacement model was established, the efficiency of thermal recovery function was adopted in the model, but it still ignored the steam overlap [7]. Neuman established the steam frontal mathematical model which considered gravity overlap, as well as made two important assumptions [8]. But the mobility ratio was set as 0 in the model ,in fact ,due to the bigger oil viscosity or smaller steam injection rate, mobility ratio is not 0 and sometimes even tend to be 1. At present, the research of vapor phase front's migration rules in steam assisted gravity drainage still stay at the stage of paper describing [9, 10]. In order to surmount these challenges, the theory of percolation mechanics are introduced, combined with the development characteristics of steam assisted gravity drainage, we do workings such as establishing the mathematical model of pressure field and the vapor phase equation of symmetry element, displaying the migration rules of vapor phase front macroscopically by combination of difference discrete principle and numeric calculation. The achievements perfect the three-dimensional development seepage theory of heavy oil and provide theoretical guidance to the improvement of recovery factor of heavy oil reservoir.

2. MATHEMATICAL MODEL

2.1. Van Lookren Steam Overlap Theory

The equation was established by Van Lookren that describes the degree of overlap which can be predicted in steam flooding [11]. The equation of steam overlap degree was based on Darcy's law basic principle, using the presumption of stratified flow [12]. The degree of steam overlap is represented by dimensionless coefficient R_s, R_s 's definition formula is:

$$R_s = \sqrt{\frac{v_{ai} v_a}{B^2 \pi \Delta \rho g K_a}} \tag{1}$$

where R_s — the dimensionless coefficient; v_a — the dynamic viscosity of steam, m^2/s; v_{ai} — injection rate of steam, kg/s; ρ — density difference of oil and steam, kg/m^3; g — gravitational acceleration, m/s^2; K_a — permeability of the steam zone, μm^2; B — reservoir total thickness, m.

The influence of R_s on the steam zone interface's waveform is shown in Figure 1. When the value of R_s is small, the flowing of steam will be limited on the top of the reservoir, front dip angle become small. With the value of R_s increasing, steam front tends to be vertical, the steam zone will be thickness, improving the steam sweep volume and recovery factor finally [13].

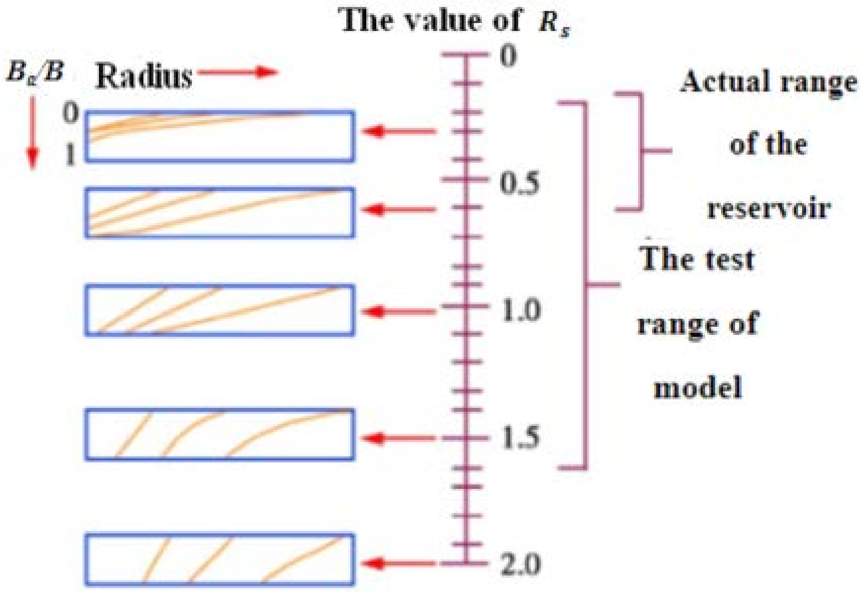


Figure 1. The relationship between steam overlap coefficient R_s and shape of vapor phase front

2.2. Analyzing the Steam Overlap Coefficient

We can get the relationship between steam overlap coefficient R_s and the shape of vapor phase front from equation (1), then analyzing the dimension of R_s by shortcut method [14].

$$R_s^2 \longleftrightarrow constant \times \frac{p_i}{(\rho_o - \rho_s)gB} \tag{2}$$

where p_i — injection pressure, Pa.

We can get from equation (2) that R_s can be seen as the ratio between steam injection pressure and gravity potential difference of gas-liquid phase.

In figure 2, supposing that steam has been injected into equal thickness reservoir, with the increasing of injection pressure, the value of R_s gets larger, steam front angle trend to be vertical, when steam injection pressure is constant, the values of R_s and front dip angle are both declining with the rise of reservoir thickness's value, and the effect of steam overlap is more serious [15].

2.3. Prediction model of steam front which considering pseudo-mobility ratio

In actual reservoir, due to the bigger oil viscosity or smaller steam injection rate, pseudo-mobility ratio is always larger, in this situation, the way that using the largest shape factor optimize steam injection parameters is restricted [16]. In view of this situation, we adopt mathematics method to study the prediction model of steam drive front which considers that pseudo-mobility ratio is not 0. At last, we find that increasing gas injection rate can achieve that the value of pseudo-mobility ratio and degree of steam overlap is decreasing respectively, even improving the sweep efficiency of frontal displacement.

The assumptions of model: (1) The homogeneous individual reservoir is equal-thickness; (2) Do not consider the cracks [17]; (3) Thermal conductivity at the top or bottom is equal [18]; (4) Well network is five-point scheme.

Because of steam overlap, we should consider the steam balance at radial and longitudinal direction [19]. At last, the equation of steam drive front has been established, following as equation (3).

$$\frac{B_a}{R_s B} = \left[\left(\ln(\frac{r_e}{r} - \frac{1}{2} + \frac{r^2}{2r_e^2}\right)(1 - M^*)\right]^{\frac{1}{2}} \tag{3}$$

where M^* — pseudo-mobility ratio; R_s — the dimensionless coefficient, r — the radial distance from steam injection point, m; r_e —the radial distance of somewhere from steam injection point, m; B_a —thickness of steam zone, m.

2.4. The vapor phase equation of symmetry elements in steam assisted gravity drainage

According to the well network which is assumed in an ideal and the results of steam overlap, based on the source and sink relationship theory [20], we can get the vapor phase function of symmetry elements in steam assisted gravity drainage, the equation is following as equation (4):

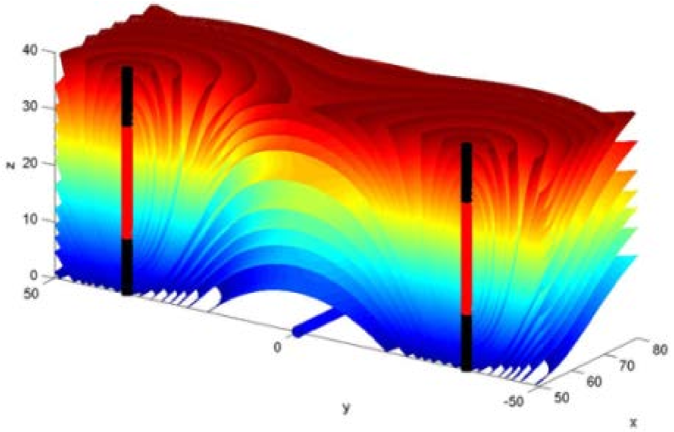
$$\begin{gathered} \Phi = \Phi_H + \Phi_{V_1} + \Phi_{V_2} \\ = \frac{Q_{V_2}}{4\pi L_{V_2}} \ln \frac{\sqrt{x^2+(y+35)^2+(10-z)^2}+(10-z)}{\sqrt{x^2+(y+35)^2+(30-z)^2}+(30-z)} + \frac{Q_{V_1}}{4\pi L_{V_1}} \ln \frac{\sqrt{x^2+(y-35)^2+(10-z)^2}+(10-z)}{\sqrt{x^2+(y-35)^2+(30-z)^2}+(30-z)} \\ - \frac{Q_H}{4\pi L_{H_1}} \ln \frac{\sqrt{(x-20)^2+y^2+z^2}+\sqrt{(x+20)^2+y^2+z^2}-40}{\sqrt{(x-20)^2+y^2+z^2}+\sqrt{(x+20)^2+y^2+z^2}+40} + (\rho_s - \rho_w)gz + C \end{gathered} \tag{4}$$

where Φ — total potential of symmetry elements; Φ_{H} — potential of horizontal well; Φ_{v1}, Φ_{v2} — potential of vertical wells; Q_{v1}, Q_{v2} — produced flowrate of vertical wells, m3/h; ρ_s, ρ_{o} — density of steam and oil, kg/m3.

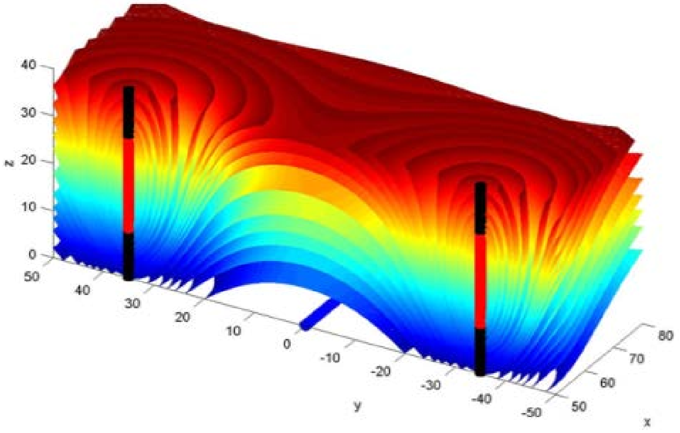
3. ANALYSING THE CALCULATION RESULTS OF THE MODEL

3.1. The influence of production factor to the steam migration rules of SAGD symmetry elements

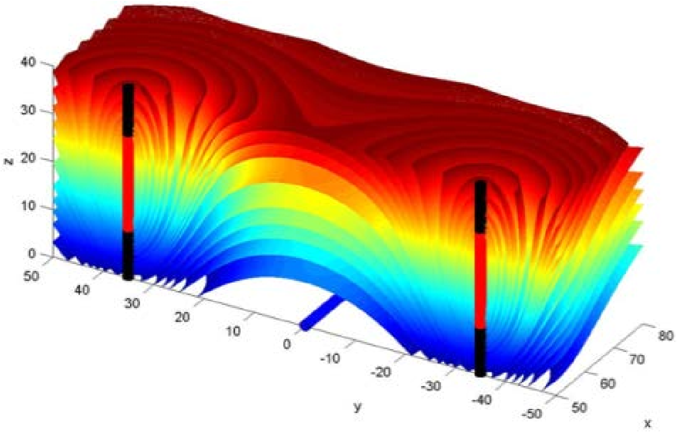
In order to ensure the migration rules of vapor front and the volume of steam sweep which are influenced by production factor, we adopt the method that fixing the structure of well pattern and the position of perforating, as well as remaining the injection volume constant (the injection volume is 100 t/d), then changing the mass production of horizontal well (240 t/d, 230 t/d, 220 t/d, 210 t/d).



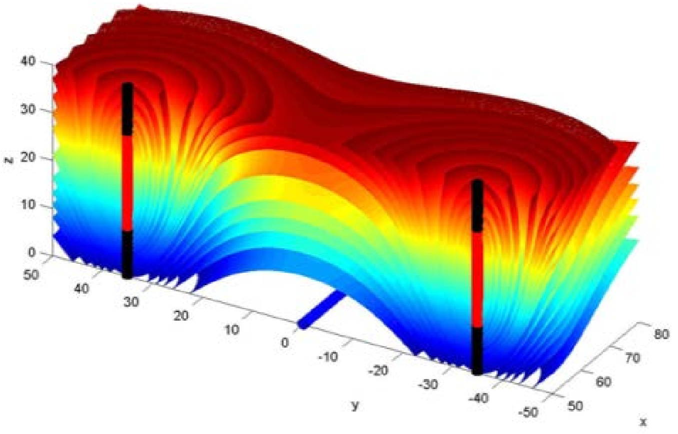
(a) Production factor 1.2



(b) Production factor



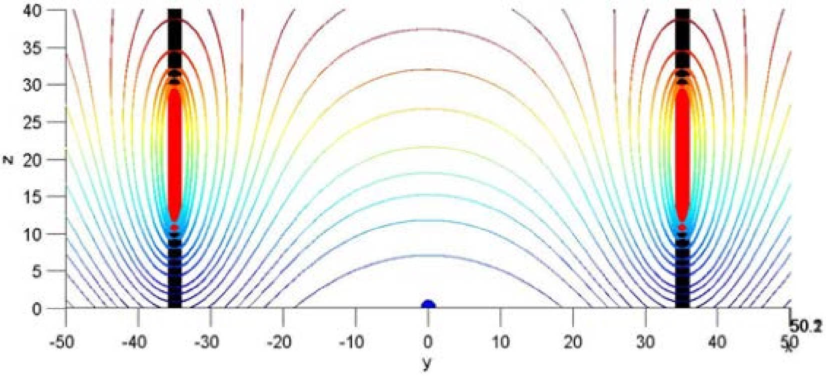
(c) Production factor 1.1



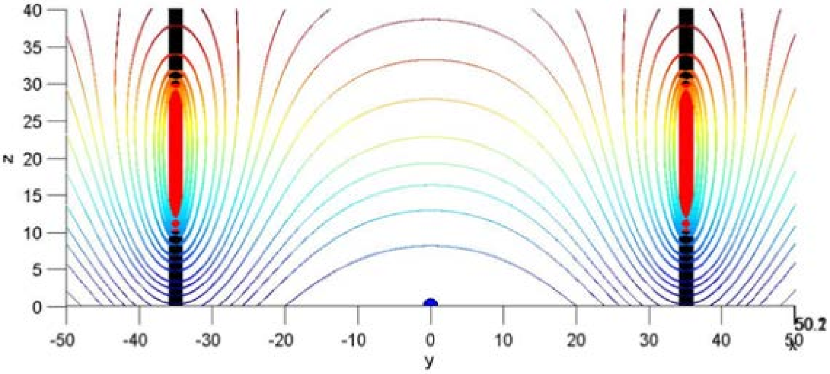
(d) Production factor 1.05

Figure 2. Comparison diagram of steam cluster in SAGD symmetry elements

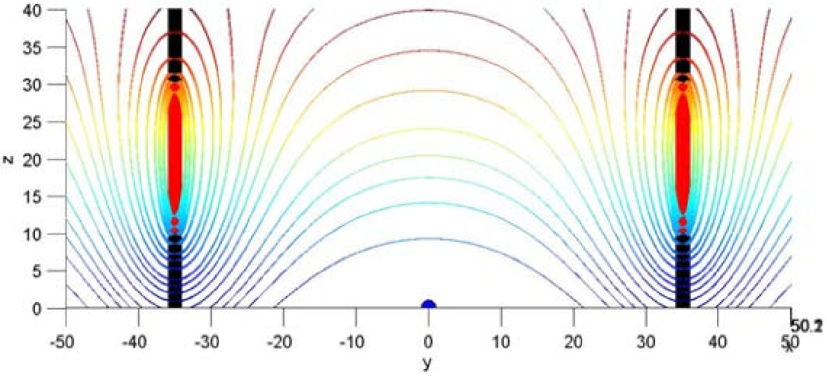
The migration trends of vapor phase front in SAGD symmetry elements are intuitively shown in Figure 2 (The results consider the action of steam overlap and shape factor of steam overlap). In the preliminary period of steam chamber growth, owing to the existence of the action of longitudinal steam overlap, the steam is expanded along the opposite direction of horizontal production well [21]. It can successfully avoid the happening of extensive and downward gas breakthrough of steam. The action of steam overlap makes the steam chamber's growth upward, the compound action of gravity and the pumping of horizontal well cause the steam's growth in the horizontal direction or ramp up after the steam cluster reach to the top of reservoir [22]. At last, the compound action of gravity and the pumping of horizontal well, as well as the displacement of steam contribute to the growth of steam chamber downward [23].



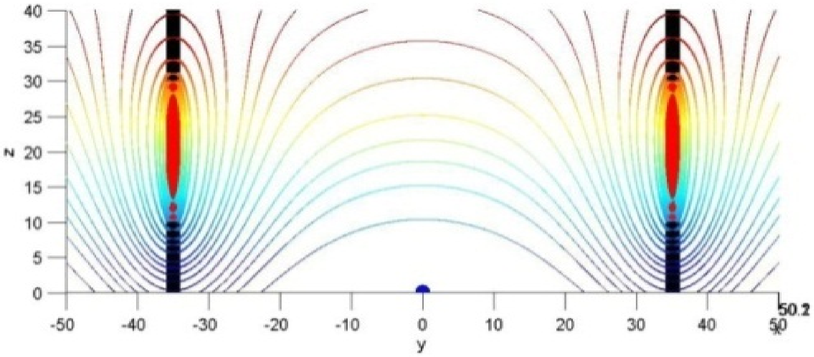
(a) Production factor 1.2



(b) Production factor 1.15



(c) Production factor 1.1



(d) Production factor 1.05

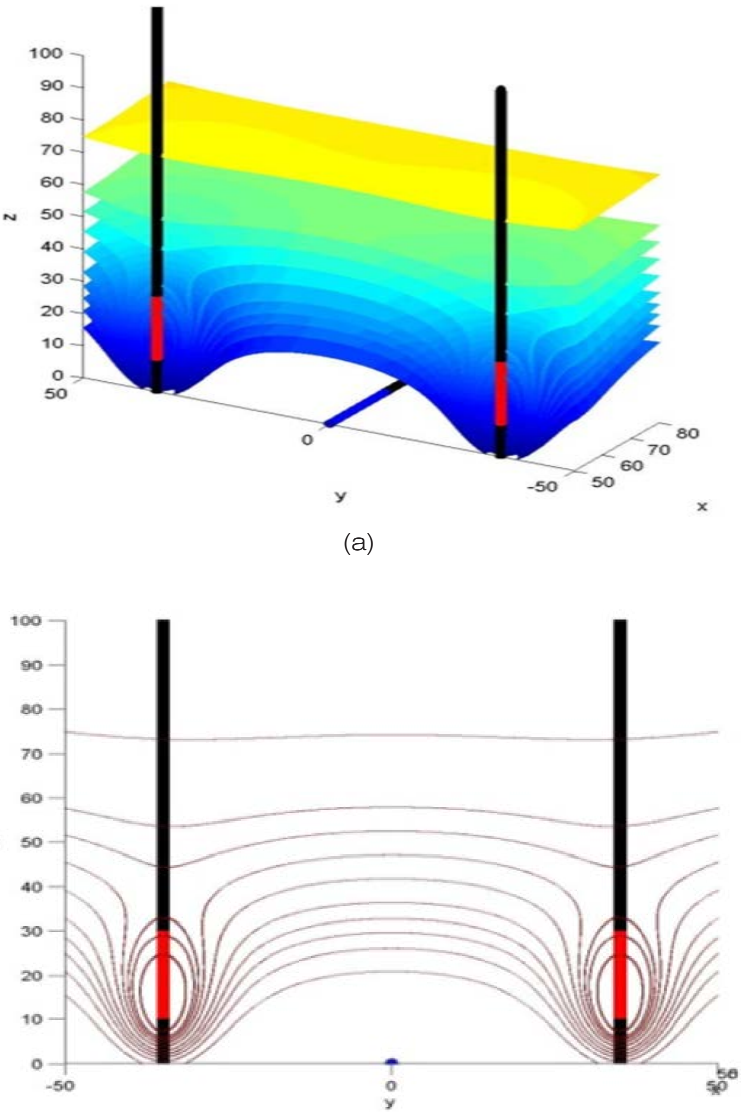
Figure 3. Comparison diagram of steam cluster in SAGD symmetry elements profile map)

The steam volume of SAGD symmetry elements on conditions that production factor is different are shown in Figure 3. With the increasing of production factor in SAGD symmetry elements, the mass production of the bottom horizontal well is increased, which leads to that the action of inhibition and dragging of the bottom production well to the overlap of vapor front have been enhanced, as well as contribute to accelerate the connection of steam chamber above the horizontal injection well, increasing the steam sweep volume within the symmetry elements [24, 25].

3.2. The influence of reservoir thickness to the steam migration rules of SAGD symmetry elements

In order to study the migration rules of vapor front and the volume of steam sweep, we adopt the way that fixing the structure of well pattern and the position of perforating, considering that the reservoir thickness is 100m.

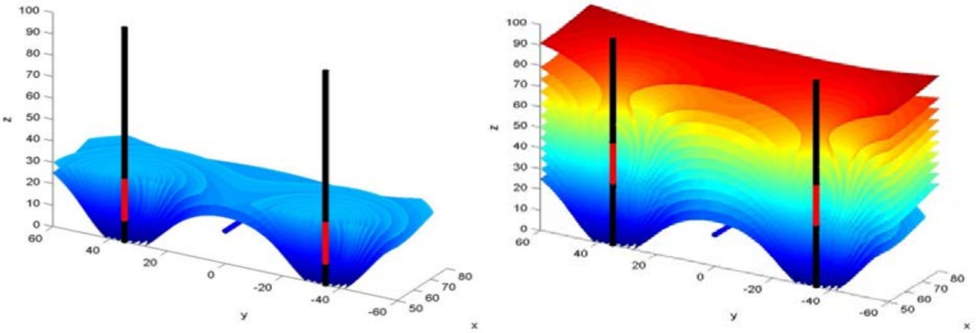
It can be seen in Figure 4 that the sweep volume of steam in SAGD symmetry elements is limited in the condition of high reservoir thickness. Although the sweep volume of steam is creased by adjusting the perforating position of vertical wells, but the heavy oil in the steam chamber can’t effectively flow into the bottom horizontal well [26]. For this kind of reservoir, we can adopt the method that adjusting the position of the bottom horizontal well as well as the perforating position of vertical wells secondary to expand the sweep volume of steam in symmetry elements, and reducing the filtration resistance of heavy oil which flow into the bottom horizontal well [27].



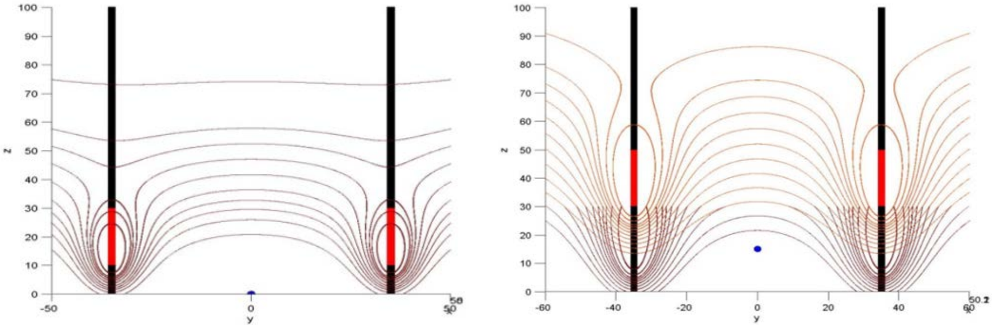
(a)

(b)

Figure 4. The sweep volume of steam in SAGD symmetry elements (The reservoir thickness is 100m)



(a) Comparison diagram of steam cluster before and after adjusting the bottom



(b) Comparison diagram of vapor front profile that before and after moving the bottom

Figure 5. Comparison diagram that before and after the bottom horizontal well's position is moved

It can be seen in Figure 5 that after the bottom horizontal well's position is moved up 15m, steam flooding is formed between vertical well and horizontal well firstly. Although controlled reserve is limited in the reservoir by this method of steam displacement, but the steam which injected from vertical well is affected by the steam overlap and preheat the area that above the horizontal well [28]. It is beneficial for the SAGD symmetry elements which are formed by adjusting the position of vertical section. Preheating oily layer above the horizontal well contributes to accelerate the connection of vertical-horizontal well and stabilize the process of oil drainage in SAGD symmetry elements [29]. It can form gravity drainage symmetry elements in the top half of oily layer by adjusting the perforation interval of vertical well. We can get the achievements that adopting the method that adjusting the perforation interval of vertical well secondary and moving up the position of horizontal well can form the stereoscopic development well pattern which are adjustable [30]. This kind of well pattern contributes to the improvement of the sweep volume of steam in SAGD symmetry elements effectively and the received reservoir thickness of single horizontal well, it even can maximum control the reserve volume of the reservoir and improve the development effect [31].

4. CONCLUSION

1. We establish the mathematical model of migration of vapor phase front, then combined with the data mapping software, displaying the migration rules of vapor phase.
2. In the development process of steam assisted gravity drainage, the increasing of production factor contributes to accelerate the connection of steam chamber above the horizontal well and improve the sweep volume of steam in the symmetry elements, improving the working degree of reservoir effectively.
3. We can adopt the method that adjusting the perforation interval of vertical well secondary and moving up the position of horizontal well for the thicker reservoir to improve the sweep situation of steam in the symmetry elements.

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