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Quantitative research on the influence of interlayer to thermal recovery horizontal wells in thick oil reservoir

Dong Liu*, Zong-Bin Liu, Jun-Ting Zhang, Jian-Min Zhu and Li-Lei Wang

Tianjin Branch of CNOOC Ltd., China National Offshore Oil Corporation, Tianjin 300459, China.

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At present, the effect of different development patterns of interlayer like the length and the longitudinal position of interlayer on thermal recovery modes such as steam stimulation (CSS) and steam flooding (SF) is still a qualitative understanding, and there is no systematic study yet. Therefore, it is difficult to control the thermal production of thick oil reservoirs according to different interlayer patterns. In order to quantitatively analyze the influence of interlayer distribution pattern on steam huff and puff and steam flooding of horizontal wells in thick heavy oil reservoir, a numerical simulation model was established based on typical parameters of LD21 heavy oil reservoir in Bohai in China. Through comparison and research on the different modes of development longitudinal position, development length and development scale in non-permeable interlayer and semi-permeable interlayer. The influence of interlayer on the expansion law of steam chamber and ultimate oil recovery degree during steam huff and puff and steam flooding, and the main controlling factors of interlayer influencing oil recovery were obtained. The research results can be used for reference to optimize the location of thermal wells in thick heavy oil reservoir and reduce the influence of interlayer on thermal production effect of horizontal wells.

Key words: Heavy oil reservoir; interlayer; steam huff and puff; steam flooding; recovery.

INTRODUCTION

Interlayer mainly refers to the non-permeable or relatively low permeability band which can affect the seepage of oil and gas in the reservoir (WU et al., 2011). The stable interlayer can divide the thick reservoir into several relatively independent flow units. At present, injection steam for thermal recovery is the main way to improve oil recovery in heavy oil reservoirs (Wang et al., 2006; Zhu et al., 2011; Liu et al., 2012; Ajay, 2012; Huang et al., 2013; Khansari et al., 2014;Liu, 2015; Liu et al., 2015; Sheikholeslami et al., 2016; Hou et al., 2016; Yang et al., 2016; Ma and Liu, 2018; Zhong et al., 2015; Xiong et al., 2017). Interlayer affects fluid seepage by affecting the development and expansion of steam chamber (Zhou et al., 2006; Wang et al., 2009), which has a vital impact on the thermal effect of thick heavy oil reservoirs. Previous researchers have studied the quantitative identification criteria of different types of interlayer by using core data and logging data of coring wells. Through identification, interlayer can be divided into three types: shaly interlayer, calcareous interlayer and physical interlayer (Ma 2017; Yan and Duan, 2008). The stable distribution of interlayer is a positive significance to oil and gas development,

*Corresponding author. E-mail: liudong@cnooc.com.cn. Tel:+86 022 66500871.

Table 1. Fluid parameters of Guan IV Formation in LD21 heavy oil reservoir.

Parameter name	Parameter values	Parameter name	Parameter values
Buried depth of oil reservoir /m	1500	Thermal conductivity of upper and lower caprock / J• (m•day•C))$^{-1}$	1.06×10^{3}
Original average formation pressure /MPa	14.7	Reservoir temperature /℃	54
Rock compressibility /kPa^{-1}	2.5×10^{-5}	Vertical to horizontal permeability ratio	0.3
Volumetric heat capacity of rock /J• (m3•C)$^{-1}$	2.575×10^{6}	Reservoir thickness /m	42.9
Thermal conductivity of rock / J• (m•day•C))$^{-1}$	1.634×10^{5}	Average permeability of formation /m	3109
Thermal conductivity of oil / J• (m•day•C))$^{-1}$	9.77×10^{3}	Average porosity of formation	0.33
Thermal conductivity of water / J• (m•day•C))$^{-1}$	5.99×10^{4}	Degassing oil density / g•cm^{-3}	0.98
Thermal conductivity of gas / J• (m•day•C))$^{-1}$	1.9×10^{3}	Formation oil viscosity /mPa•s	2908
Volumetric heat capacity of upper and lower caprock /J• (m^{3}•C)$^{-1}$	2.2×10^{6}	Original oil saturation /%	62
Volumetric heat capacity of interlayer /J• (m^{3}•C)$^{-1}$	1.6×10^{6}	Thermal conductivity of interlayer / J• (m•day•C))$^{-1}$	0.55×10^{5}

such as the top interlayer can prevent steam overlap upward, the bottom interlayer can prevent bottom water coning and so on, while the unstable interlayer are surrounded by more residual oil distribution, which is not conducive to development (Zhong, 2012). Some scholars take actual oilfield as an example to study the influence of interlayer on development effect in the process of steam huff and puff, steam flooding after huff and puff, steam-assisted gravity drainage, and obtain the qualitative understanding of interlayer on thermal effect (Tang, 1995; Li, 2016). Generally speaking, the study on the effect of interlayer on thermal horizontal wells is not very detailed; the range of interlayer is a qualitative understanding, which cannot meet the requirement of CSS and SF. In CSS and SF process, interlayer length and interlayer longitudinal position are very important in thick heavy oil reservoirs, which can decide the well location. In order to quantitatively analyze the influence of interlayer distribution pattern on steam huff and puff and steam flooding of horizontal wells in thick heavy oil reservoir, longitudinal position, development length and development scale in non-permeable interlayer and semi-permeable interlayer were researched. The research results can be used for reference to optimize the location of thermal wells in thick heavy oil reservoir and reduce the influence of interlayer on thermal production effect of horizontal wells.

The establishment of theoretical model

The main oil-bearing layer of LD21 heavy oil reservoir is Guantao Formation in Bohai, of which Guan IV Formation is a layered edge water reservoir with high oil viscosity (formation oil viscosity 2908 mPa·s), deep reservoir (1500 m), good reservoir physical properties (logging porosity 33.2%, logging permeability 2145mD), thick reservoir (single layer thickness 16 ~ 40 m). The energy of water is stronger (volume multiplier of water to oil is 4~11 times). By analyzing the geological reservoir characteristics of Guan IV Formation of LD21 heavy oil reservoir in Bohai oilfield, a basic model is established without interlayer. The fluid parameters and geological parameters used in the model are shown in Table 1.

Using the STARS simulator of CMG software, the grid size in *I* and *J* directions are both 20m and is 1.3m in *K* direction in the model. The number of grids in *I* direction and *J* direction is 23 and 20, respectively. The number of grids in *K* direction is 33. The total number of simulated grids is 23×20×33=15180. Longitudinally, it is composed of a set of oil layers. The 1st to 33rd layers are oil layers from top to bottom. The effective thickness of oil layers is 42.9 m. Three horizontal wells are located in the middle of the reservoir, 100m from the edge, perforation length of horizontal section t is 300m, and the well spacing is 200 m (Figure 1).

Three wells are injected steam huff and puff at the same time. The daily steam injection rate of a single well is 300 m^3/d, the cyclic steam injection is 4500 m^3, the bottom hole steam injection temperature is 340°C, the bottom hole steam quality is 0.4, keep the wells shut for 5 days after steam injection. Oil wells are simulated by three-stage control conditions: the first control condition is constant maximum liquid (150m^3/d), the second control condition is constant pressure drop (4 MPa), and the third control condition is constant minimum bottom flow pressure (3 MPa). Simulated two production processes: three wells injected steam huff and puff for seven rounds at the same time, and then the intermediate horizontal well H2 changed for steam injection, a single well daily steam injection is 300 m^3/d, bottom hole steam injection temperature is 340°C, bottom hole steam quality is 0.6. This model can be used for injection steam development of the well pattern of 1 injection 2 production; the well is

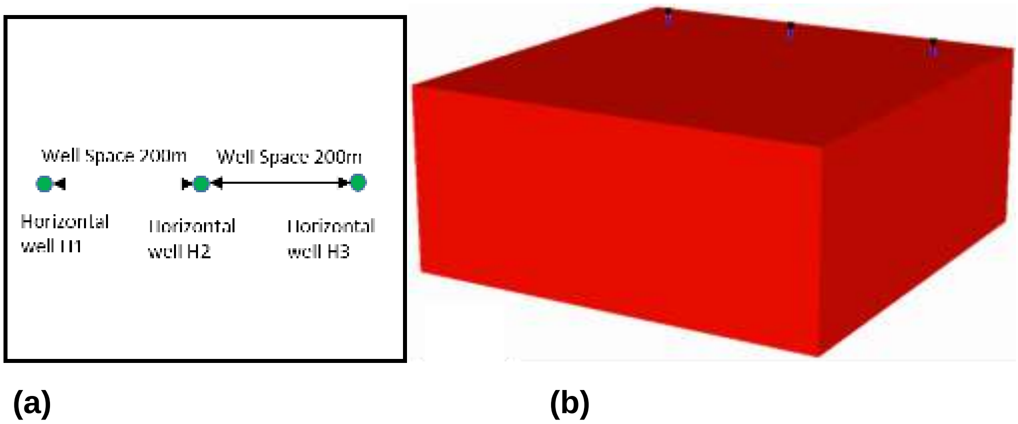


Figure 1. Schematic diagram of a typical well group numerical model I for (a) well location, (b) Original oil saturation field (S_{oi}=0.62).

Table 2. Numerical simulation design.

influence factors	Whether interlayer distributed	Specific value	Test Number
Vertical position of horizontal well	No	Upper part , middle part, Lower part	6
Non dimensional position of interlayer	Yes	0.13, 0.25, 0.38, 0.50, 0.63, 0.75,0.88,1.00	16
Non dimensional length of interlayer	Yes	0.06,0.18,0.29,0.41,0.53,0.65,0.76	14
Development scale of interlayer	Yes	Whole region distribution, Upper local distribution, Lower local distribution	6

shut-in until the entire oil field's instantaneous oil-gas ratio is below 0.15 (Table 2).

The design of test scheme

The permeability of different lithologic interlayers varies greatly, and the mudstone type has the strongest ability to seal fluid (vertical permeability is less than 1×10^{-3}μm^2), the calcareous sandstone type is next (vertical permeability is less than 2×10^{-3} μm^2), and the mixed sandstone and oil stain sandstone have the worst ability to seal fluid (vertical permeability is less than 60×10^{-3} μm^2) (Tang, 1995). The type of interlayers used in this paper is non-permeable and semi-permeable, and the corresponding permeability is 0.000×10-3 μm^2 and 0.001×10^{-3} μm^2 respectively. The schema is shown in Table 2.

The dimensionless position of interlayer is defined as the vertical distance between interlayer and horizontal well divided by the distance between horizontal well and reservoir top. The expression is as follows:

$$D_{Dm} = D_I / D_H \quad (1)$$

In the formula, D_I is for the vertical distance between the interlayer and the horizontal well, m; D_H is for the vertical distance between the horizontal well and the top of the reservoir, m.

The dimensionless length of the interlayer is defined as the length of the interlayer divided by the length of the reservoir in the plane. The expression is as follows:

$$L_{Dm} = L_I / L_H \quad (2)$$

In the formula, L_I is the length of the interlayer, m; L_H is the length of the reservoir, m.

Analysis of heating chamber expansion rule and development effect

Based on the above models and schemes, the development effects of steam huff and puff and steam flooding after steam huff and puff under different modes, such as vertical position of horizontal wells, dimensionless position of interlayer, and dimensionless thickness of interlayer and interlayer development scale

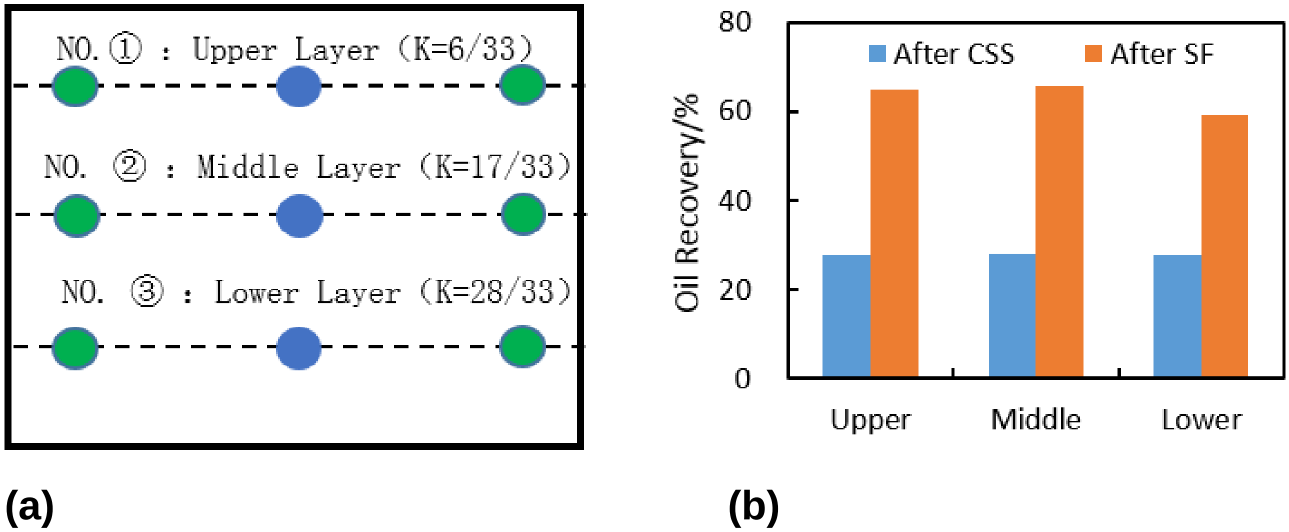


Figure 2. Influence of vertical position of horizontal well for (a) vertical location diagram, (b) development indicator diagram of different locations.

are researched respectively.

The influence of vertical position of horizontal wells

In order to determine the basic model, the best well location of thick and heavy oil reservoirs without interlayer development is researched. As shown in Figure 2a, three horizontal wells are deployed in the upper, middle and lower parts of the reservoir to obtain the oil recovery at the huff and puff stage and at the end of displacement, as shown in Figure 2. The results show that when the three wells are located in the middle of the reservoir simultaneously, the recovery degree of huff and puff stage and steam flooding stage reaches the maximum of 28.1% and 65.8%.

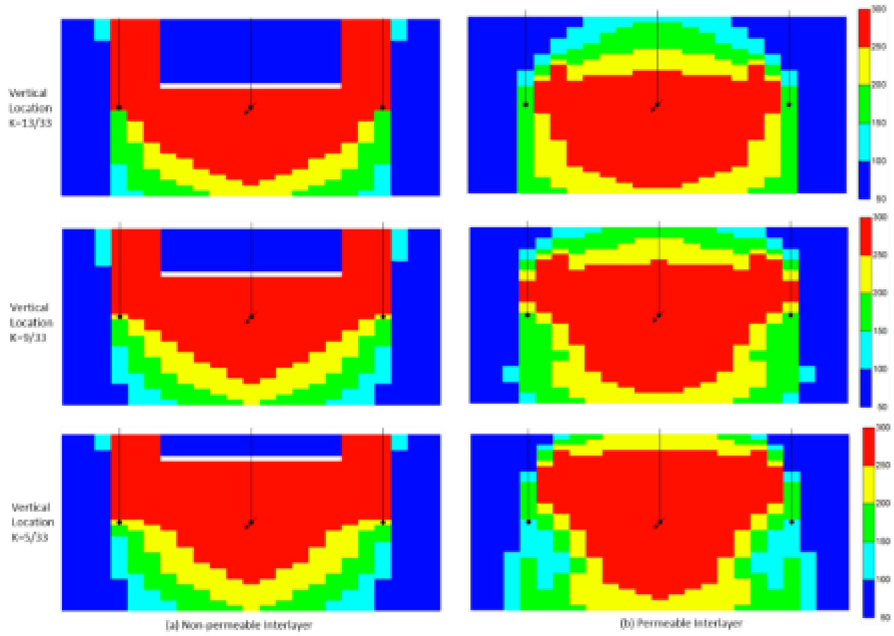
Dimensionless position of interlayer

The distance of interlayer and the vertical position of horizontal well affect the distribution and expansion of steam, and ultimately affects the heating range and oil displacement range, thus affecting the thermal recovery effect. Figure 3 is a comparison of the temperature field at the end of steam flooding after huff and puff at different interlayer positions (K = 13/33, K = 9/33, K = 5/33), the corresponding dimensionless interlayer positions (0.25, 0.50, 0.75).

Figure 3 shows that the non-permeable interlayer and permeable interlayer have different effects on the heating range. As shown in Figure 3a, for such non-permeable interlayer as argillaceous interlayer, it is difficult for the injected steam to enter the upper part of the interlayer, resulting in a lower temperature in the upper part of the interlayer at the end of development. For such semi-permeable interlayer as physical interlayer, the injected steam can heat the upper part of the interlayer, and the temperature increases significantly at the end of development, as shown in Figure 3b. It can be seen that for heat conduction and convection, the semi-permeable interlayer slows down the heat transfer, and the heat transfer performance is better than the non-permeable interlayer.

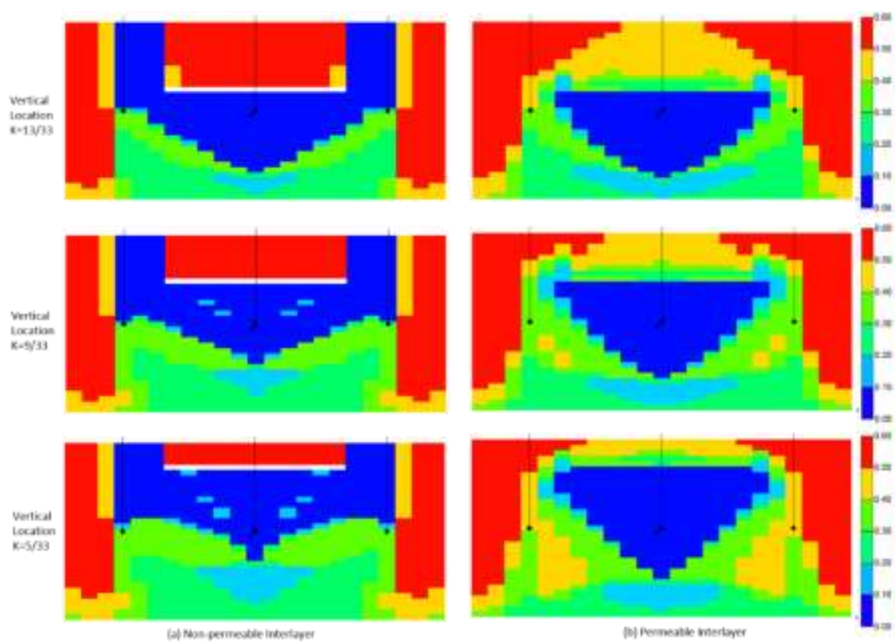
Figure 4 compares the remaining oil saturation at the end of steam flooding development at different interlayer positions. As shown in Figure 4a, for a non-permeable interlayer, there is obvious residual oil accumulation area at the upper part of the interlayer, indicating that the interlayer prevents fluid flow in the upper part of the interlayer. For a semi-permeable interlayer, the upper part of the interlayer is available, showing that the remaining oil saturation is lower than the original oil saturation, as shown in Figure 4b. It can be seen that the reservoirs located at the upper and lower parts of the semi-permeable interlayer can contribute to the oil production.

Figure 5 is a development index for different interlayer positions. Figure 5a shows that with the increase of dimensionless position of interlayer, the recovery degree increases gradually in huff and puff stage. Figure 5b shows that the recovery degree increases first and then decreases at the end of steam flooding whether it is non-permeable interlayer or semi-permeable interlayer. When the development position of interlayer changes from K=13/33 to K=5/33, the oil recovery degree of CSS increases from 26.3 to 27.7%. For steam flooding, the final recovery degree tends to be consistent.



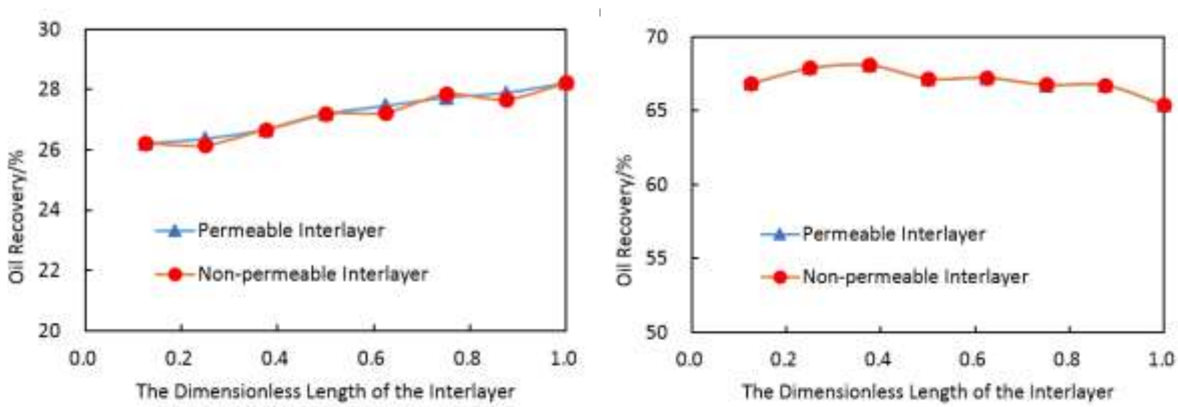
(a) **(b)**

Figure 3. Temperature field at the end of steam flooding of different interlayer locations for (a) Non-permeable Interlayer, (b) Permeable Interlayer. The red area is heated oil, the blue area is not heated oil.



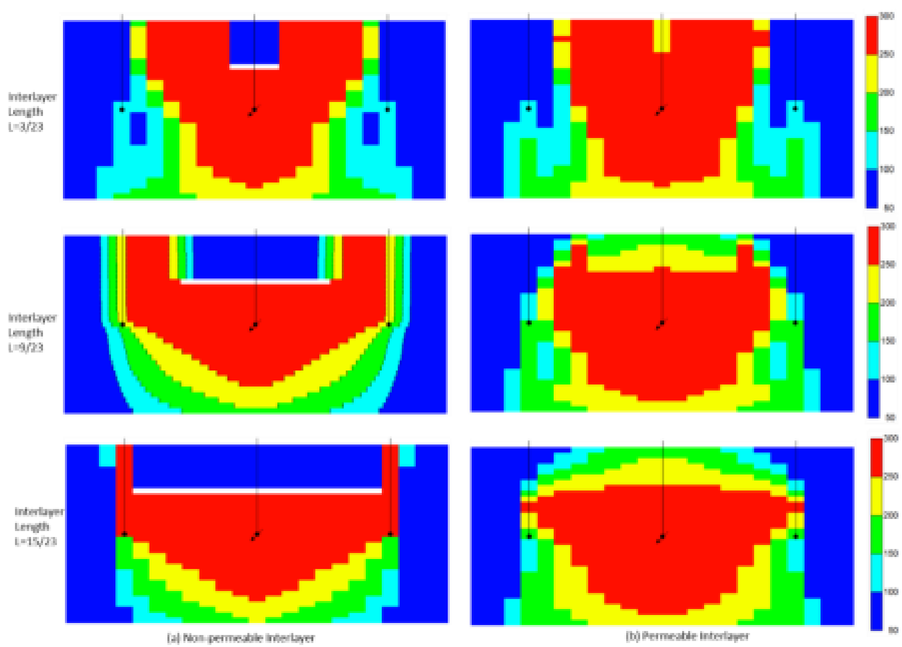
(a) **(b)**

Figure 4. Remaining oil saturation field at the end of steam flooding of different interlayer locations for (a) Non-permeable Interlayer, (b) Permeable Interlayer. The blue area is less remaining oil saturation, the red area means larger remaining oil saturation.



(a) **(b)**

Figure 5. Development indicators of different interlayer locations for (a) cycle steam stimulation for 7 cycle, (b) after steam flooding.



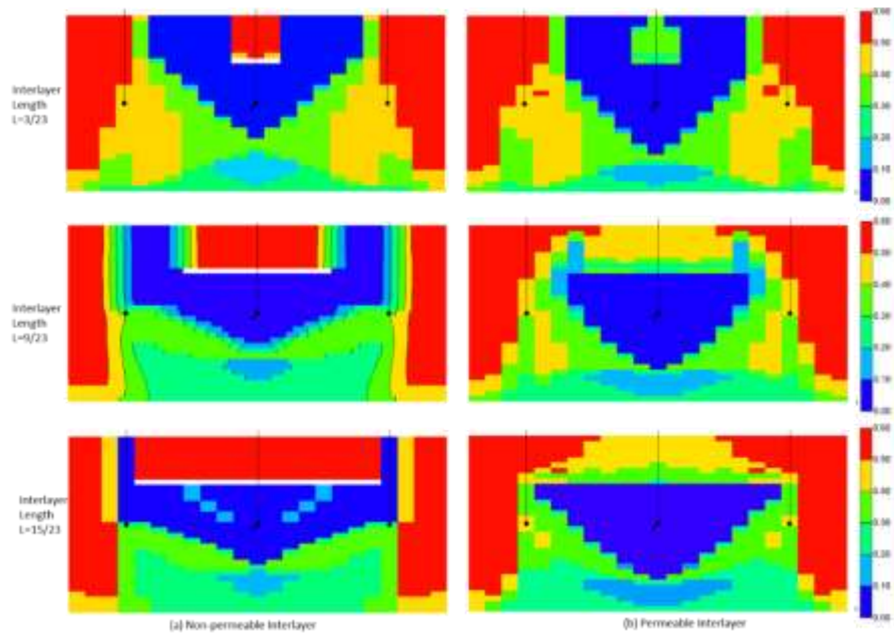
(a) **(b)**

Figure 6. Temperature field at the end of steam flooding of different interlayer lengths for (a) Non-permeable Interlayer, (b) Permeable Interlayer. The red area is heated oil, the blue area is not heated oil.

The dimensionless length of interlayer

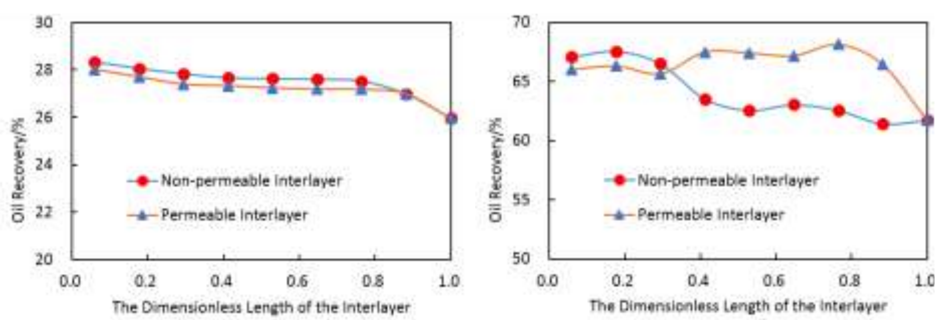
The dimensionless length of interlayer affects the distribution and expansion of steam, and affects the heating range and oil displacement range, thus affecting the thermal recovery effect. Figure 6 is a comparison chart of temperature field at the end of steam drive after huff and puff with different interlayer lengths (L= 3, L= 9, L= 15), corresponding dimensionless interlayer lengths (0.18, 0.53, 0.88).

Figure 6 shows that the longer the interlayer develops, the more obvious the compression of the heating range and the wider the lateral expansion range of the steam injection. When the interlayer is short, the injected steam



(a) **(b)**

Figure 7. Remaining oil saturation field at the end of steam flooding of different interlayer lengths for (a) Non-permeable Interlayer, (b) Permeable Interlayer. The blue area is less remaining oil saturation, the red area means larger remaining oil saturation.



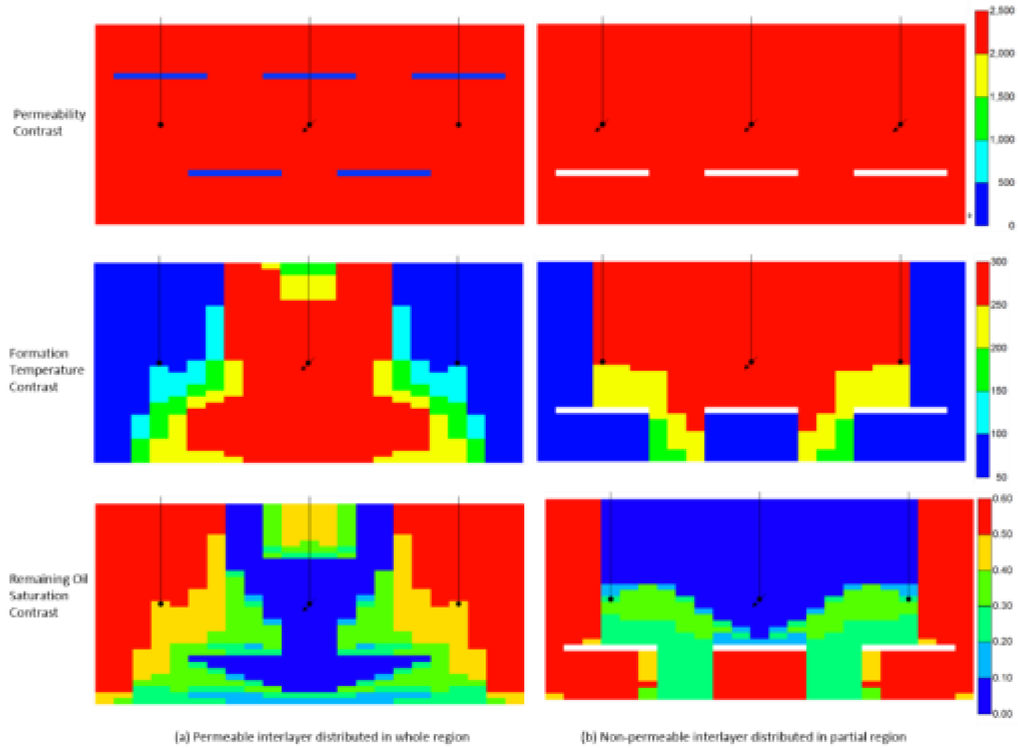
(a) **(b)**

Figure 8. Development indicators of different interlayer lengths for (a) cycle steam stimulation for 7 cycle, (b) after steam flooding 4.4 development scale of interlayer.

mainly extents to the top of the reservoir and then expands laterally; when the interlayer is long, the injected steam quickly reaches the top of the interlayer, and then expands laterally, increasing the lateral sweep volume. For non-permeable and semi-permeable interlayer, the vertical sweep coefficient of semi-permeable interlayer is higher, while the transverse sweep range is smaller. The difference of heating mode will lead to the difference between the seepage law of oil and the distribution of remaining oil.

Figure 7 compares the remaining oil saturation field at the end of the development of steam drive with different interlayer lengths. As shown in Figure 7a, for a non-permeable interlayer, there is obvious residual oil accumulation area at the upper part of the interlayer, indicating that the interlayer prevent fluid flow in the upper part of the interlayer. For a semi-permeable interlayer, the upper part of the interlayer is available, as shown in Figure 7b.

Figure 8 is a development index for different interlayer lengths. Figure 8a shows that with the increase of dimensionless length of interlayer, the recovery degree



(a) **(b)**

Figure 9. Permeability, formation temperature, remaining oil saturation field diagram comparison at the end of steam flooding of different interlayer development scales for (a) Permeable interlayer distributed in whole region, (b) Non-permeable interlayer distributed in partial region.

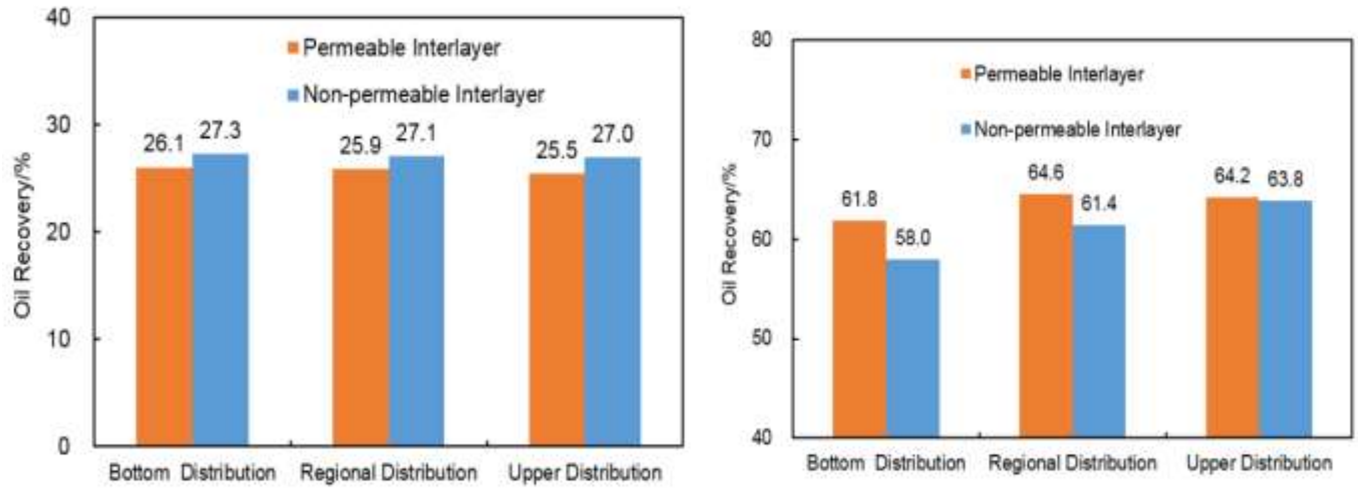
decreases gradually in huff and puff stage whether it is non-permeable interlayer or semi-permeable interlayer. When the dimensionless length of interlayer increases from 0.06 to 1.00, the recovery degree decreases from 28.3 to 26.0% during huff and puff stage. For steam flooding after huff and puff, the recovery degree of semi-permeable interlayer decreases from 67.5 to 61.7%, while the recovery degree of non-permeable interlayer first decreases and then keep stable.

Figure 9 is a comparison of permeability field, formation temperature field and residual oil saturation field of different interlayer development scale. It can be seen that the different development scale of interlayer affects the distribution of temperature field and remaining oil saturation field. Figure 10 (a) shows that for huff and puff development, the recovery degree of non-permeable interlayer is slightly higher than permeable interlayer. The main reason is that the heating range of huff and puff is limited, and the influence of interlayer is not obvious. However, with the development of production, the recovery degree of non-permeable interlayer is lower than permeable interlayer while steam flooding after huff and puff. Especially when the interlayer is distributed at the bottom or in the whole area, the difference of recovery degree between them is 3.2-3.8%.

The influence of interlayer development on well location design

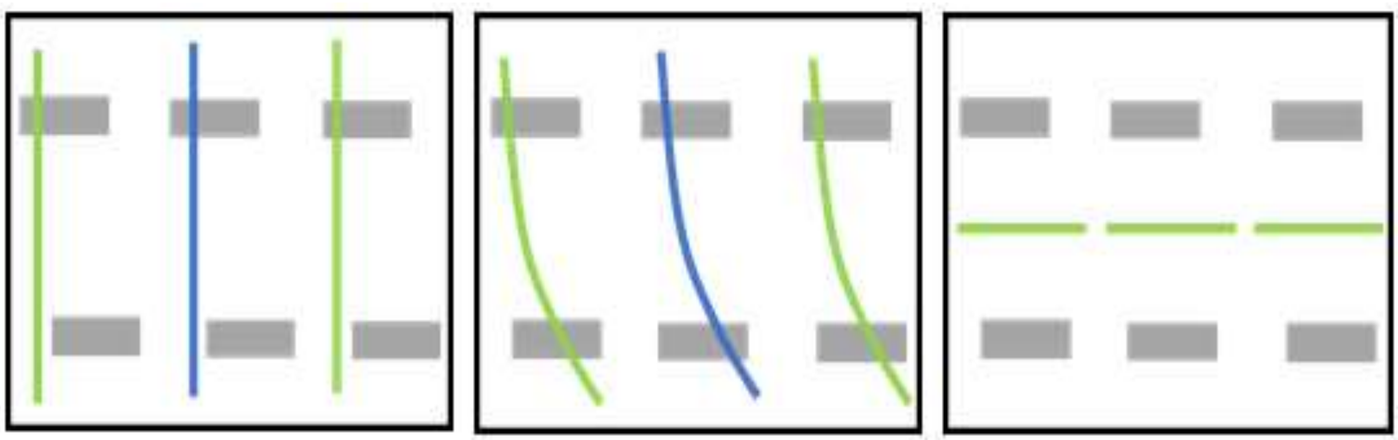
In the case of interlayer distributed in the whole area, there are three well distribution modes: 1) vertical well passes through one set of interlayer; 2) directional well obliquely passes through two sets of interlayer; 3) horizontal well deployed between two sets of interlayer, as shown in Figure 11.

Table 3 is the recovery degree of huff and puff stages and the end of steam drive at different well location pattern. Table 3 shows that the more passing through the interlayer, the better the development effect for directional well development. The recovery degree of directional well passing through two sets of interlayer is higher than that vertical well passing through one set of interlayer. Directional well can get 5.6 percentage point and 3.4 percentage point higher oil recovery than that of vertical well for huff and puff and steam flooding, respectively. Horizontal wells have the best recovery effect, and the recovery degree can reach 28.9% in huff



(a) (b)

Figure 10. Development indicators of different interlayer models for (a) cycle steam stimulation for 7 cycle, (b) after steam flooding.



(a) (b) (c)

Figure 11. Different well type of interlayer distributed in whole region for (a) vertical well, (b) directional well, (c) horizontal well.

Table 3. Comparison of recovery degree for different well pattern of interlayer distributed in the whole area.

Case name	Pass through interlayer	Steam injection rate	Injection-production ratio	Huff and puff stage recovery degree	Steam drive end recovery degree	Recovery degree added value
	/	/ （m^3/d）	/	/%	/%	/%
Vertical well	Pass through one set of interlayer	300	1.2	15.0	43.5	/
Directional well	Pass through two sets of interlayer	300	1.2	20.6	46.9	3.4
Horizontal well	Not pass through interlayer	300	1.2	28.9	59.7	16.2

and puff stage, 59.7% at the end of steam flooding. It can get 13.9 percentage point and 16.2 percentage point higher oil recovery than that of vertical well for huff and puff and steam flooding, respectively.

CONCLUSION AND RECOMMENDATIONS

(1) When there is no interlayer, the horizontal wells are located in the middle of the reservoir, the recovery degree of the huff and puff stage and steam drive stage reaches the maximum of 28.1% and 65.8% respectively. Therefore, it is suggested that thermal recovery horizontal wells should be deployed in the middle part of reservoirs for the reservoir of no interlayer.

(2) Mudstone interlayer (non-permeable interlayer) and physical interlayer (semi-permeable interlayer) have different effects on thermal recovery. For the semi-permeable interlayer, the upper part of the interlayer can be developed, but the non-permeable interlayer cannot be developed.

(3) With the increase of dimensionless position of the interlayer, the recovery degree increases gradually in huff and puff stage, and the recovery degree increases first and then decreases at the end of steam flooding whether it is non-permeable interlayer or semi-permeable interlayer.

(4) The longer the interlayer develops, the more obvious the compression of the heating range and the wider the lateral expansion range of the steam injection. When the dimensionless length of interlayer increases from 0.06 to 1.00, the recovery degree decreases from 28.3 to 26.0% during huff and puff stage. For steam flooding, the recovery degree of physical interlayer decreases from 67.5 to 61.7%.

(5) For two sets of discontinuous interlayers, horizontal wells are the best, directional wells are the second and vertical wells are the worst. For directional wells, the more interlayers are passed through by directional wells, the effect is the better.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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