Steam Flooding is Feasible and Capable to Enhance Oil Production in SaBei Transition-Zone

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Abstract

The use of steamflooding as a tertiary recovery method for light-oil reservoirs after waterflood has been of interest in recent years. Although steamflooding applied to heavy-oil reservoirs has been a fully proven method, the technology of applying it to light-oil reservoirs, especially those that have been watered out, is still in its infancy. This paper presents a comprehensive simulation study on the use of steamflooding after waterflood in light-oil reservoirs, to analyze the recovery mechanisms and the conditions which will be suitable for steamflooding. Compared to the actual oil properties and reservoir characteristics in SaBei Transition-Zone in Daqing oil-field, it has been proved the feasibility of steamflooding in this area. This study will be beneficial for the enhancing recovery, especially for the whole Transition-Zone area in Daqing oil-field. It will provide the technical reference and guidelines as well.

Keywords: Steamflood; Feasibility; Light-oil; Reservoirs

1. Introduction

It has been waterflooded more than 30 years in SaBei Transition-Zone in Daqing oil-field. And now the reservoir is in the stage of high water saturation. Due to the worse oil characteristic and rock properties, especially the higher oil viscosity, nearly 108.54mpas, so the exploitation degree was lower, less than 20%. But there is still remaining oil could be provided for recovery, while it is difficult to obtain the higher recovery rate by using of conventional methods. So it is necessarily to take advantage of thermal recovery technology for enhancing oil recovery.

This work starts with a 40-acre [16.2ha] waterflood that is later converted to steamfloods with smaller patterns. A three-dimensional multiphase thermal recovery simulator with nine-point finite-difference formulation was used so that the grid orientation effect was greatly reduced in the simulation of steamfloods in five- and nine-spot patterns. A large number of reservoir oil and rock properties were considered. The following were developed: general observations on the process, guidelines for selecting candidates for steamflooding after waterflood, and relative importance of the various key mechanisms to the light-oil steamflood.
2. Oil Property

The base case assumes Crude B (33.0°API[0.86g/cm³], 60% distillable). To obtain the effect of oil property on steamflood performance, two other crudes were used—i.e., Crude A (26°API [0.90g/cm³], 35% distillable) and Crude C (40.1°API[0.83g/cm³], 85% distillable). Each of these crudes was assumed to consist of three components—B300, B500, and heavy oil. B300 and B500 are distillable. B300 represents the fraction having a boiling point range between 200 and 400°F [93 and 204°C] with an average boiling point of 300°F [149°C]. Similarly, B500 refers to the fraction boiling between 400 and 600°F [204 and 316°C] with an average boiling point of 500°F [260°C]. The heavy-oil component boils above 600°F [316°C] and is considered to be not distillable.

Simulation results for these three crudes shows, where project life, cumulative SOR, and steamflood oil recovery are plotted vs. oil gravity. This figure shows that project life remains constant at 4 years when oil gravity changes from 26.0 to 33.0°API [0.90 to 0.86g/cm³]. Further increase in oil gravity increases the project life. The cumulative SOR for Crude A is as high as 11.2bbl/bbl[11.2 m³/m³], and the oil recovery is only 39%, making it an unlikely candidate for steamflooding. As oil gravity increases to 33.0°API[0.86g/cm³] (Crude B), the cumulative SOR decreases to 8.5bbl/bbl [8.5m³/m³]. The oil recovery, however, reaches the respectable level of 53.4% OIP at start.

It is important to know that the cumulative SOR is reduced to 7.1bbl/bbl[7.1 m³/m³] as the gravity increases further to 40.1°[0.83g/cm³] (Crude C). The expected oil recovery is even more exciting, amounting to 84.5% OIP at start. It has been shown that the total oil recovery from both waterflood and steamflood, based on the OOIP, is 41.2+49.7=90.9% OOIP. Only 9.1% of the original oil will remain unproduced after waterflood and steamflood.

The higher the oil gravity, the better the steamflood performance. To avoid an exceeding high cumulative SOR, a preferred candidate for steamflooding should have an oil gravity of 33°API or higher [0.86 g/m³ or lower] with at least 60% distillable by liquid volume.

As steamflooding proceeds, the composition of the produced oil changes constantly. For Crude A, the oil produced in the early stage of steamflood has the same composition as the reservoir oil, having 35% distillable components (B300 and B500) and 65% heavy oil. At the end of 4 years of steamflood, the percentage of distillable oil increases to 57%, whereas that of the heavy oil drops to 43%. For Crude B, the percentage of distillable components in the produced oil increases from 60% initially to 89% at the end of 4 years of operation. For Crude C, which contains 85% distillable oil initially, the produced oil is virtually 100% distillable at the end of 5 years.

The oil gravity of the produced oil also changes with time. Crude A, originally of 26.0°API[0.90g/cm³], produces 29.8°API[0.88g/cm³] oil at the end of 4 years. For Crude B, the oil gravity increases from the original 33.0 to 41.5°API [0.86 to 0.82g/cm³] at the end of 4 years. Crude C has a gravity of 40.1°API[0.83g/cm³] initially. At the end of 5 years, the gravity of the produced oil increases to 42.5°API [0.81g/cm³].

3. Reservoir Thickness

The base case assumes a thickness of 20 ft [6.1m]. Runs were also made with thicknesses of 30, 40, and 60 ft [9.1, 12.2 and 18.3]. Another run with a thickness of 10 ft [3.1m] is not reported here because the instantaneous SOR is higher than 10 bbl/bbl [10 m³/m³] all the way, indicating that a thin reservoir like this may be a highly unlikely candidate for steamflooding after waterflood. With the change in thickness, the water and steam injection rates were changed proportionately so that the rates per PV stay constant. This approach could have been biased against very thin reservoirs because higher steam rates are needed to offset the higher percent heat losses.
It has been shown that project life is shortened with an increase in reservoir thickness. The cumulative SOR decreases rapidly when the reservoir thickness increases from 20 to 30 ft [6.1 to 9.1m]. Although a thickness of 20 ft [6.1m] gives a cumulative SOR of 8.5 bbl/bbl, not favorable, the cumulative SOR is lowered to 5.8bbl/bbl, well within the favorable range when the thickness is increased to 30 ft [9.1m]. When the thickness is increased further to 40 ft [12.2m] or beyond, the cumulative SOR can reach as low as 4.7 to 4.8bbl/bbl [4.7 to 4.8 m³/m³], the lowest level among all the cases studied in this work. With the increase in thickness from 20 to 30 ft [6.1 to 9.1m], the oil recovery jumps from 53.4% to 62% OIP at start. Further increase in thickness, however, does not bring about further decrease in cumulative SOR or substantially higher oil recovery.

A candidate for steamflooding should preferably have a minimum thickness of 20 ft [6.1m].

4. **Porosity**

Porosity is important in determining steamflood performance. For the first, it is a part of the porosity/oil saturation product. The higher the porosity, the higher the OIP. Second, a higher porosity means a smaller amount of solid matrix that needs to be heated. This should hold true for steamflooding in both light- and heavy-oil reservoirs.

The base case has a porosity of 30%. Runs were also made with porosities of 20 and 40%. With the change in porosity, the water and steam injection rates were proportionately changed so that the rates per PV stay constant. The results show that, with the porosity lowered from 30 to 20%, the project life is shortened, and the cumulative SOR soars to an uneconomical level of 15.0bbl/bbl [15.0 m³/m³], the highest among all the cases studied in this work. At the same time, the oil recovery plunges to 15.1% OIP at start, the lowest among all the cases included in this study. A porosity as low as 20% makes the reservoir an exceedingly unlikely candidate for steamflooding. When the porosity is increased from 30 to 40%, the project life is changed slightly. The cumulative SOR is lowered to a comfortable level of 6.5bbl/bbl [6.5 m³/m³], while oil recovery increases to 63.2%.

Reservoirs with a porosity of 30% or greater will make good candidates for steamflooding after waterflood.

5. **Residual Oil Saturation to Water**

Residual oil saturation to water, S_orw, an endpoint on the curve for relative permeability to water, is not itself the remaining oil saturation after waterflood. However, it provides a lower limit to the oil saturations remaining anywhere in the reservoir after water flood. This value, associated with the porosity, determines the amount of OIP when steamflood starts. A higher S_orw, therefore, favors steamflood.

The S_orw assumed in the base case is 40%. Two other cases were assumed with S_orw = 30 and 50%. The project life increases with S_orw. Similar to the effect of porosity, the cumulative SOR decreases and the oil recovery increases with an increase in S_orw. The only difference is that the effects of S_orw on these two performance variables are not as drastic as those of porosity. This may be attributed to the fact that the effect of porosity includes the heating up of the solid matrix, whereas the effect of S_orw does not.

A low S_orw at the reservoir temperature means a low saturation of the remaining oil after waterflood and a low OIP before steamflood starts. A good candidate for steamflooding should have an S_orw of 40% or higher.
6. Permeability

The base case assumes a uniform permeability of 1000 md. Other runs were made with permeabilities of 200, 500, and 3000 md. The effect of permeability is relatively minor. The cumulative SOR does increase sharply, however, when the permeability is reduced to lower than 500 md. The oil recovery is reduced accordingly.

Reservoirs with a permeability of 200 md or less should be avoided when candidates for steamflooding after waterflood are selected.

7. Permeability Variation

While all the other runs used three equal layers to represent the reservoir thickness, the runs made for the permeability variation used five equal layers to get a better description of the variation. Permeability of the various layers was chosen assuming a permeability variation of 0.7, with a geometric mean of 1000 md. Two of the variations involve systematic ordering, one for increasing downward and another for increasing upward. The other two are random variations.

Table 1: Reservoir Oil and Rock Properties in SaBei Transition-Zone

| Oil property | Criterias for steamflood | Actual oil and rock properties in SaBei Area |
|--------------|---------------------------|---------------------------------------------|
| Reservoir thickness, m | >6.1 m (20 ft) | 10—15 m |
| Porosity, % | ≥30% | 27.4% |
| SOR, % | ≥40% | 36.65% |
| Permeability, md | >200 md | 274 md |
| Permeability variation | Increasing downward | Increasing downward |

When the permeability changes from uniform distribution to systematically increasing downward, the project life for waterflood more than doubled, increasing from 14 to 36 years. The most remarkable effect of permeability variation lies in the oil recovery, which increases from 52.1 to 64.4% OIP at start. This is understandable because higher permeability at the bottom preferentially reduces the oil saturation at the bottom during the waterflood phase, leaving more oil to be recovered in the upper part during the subsequent steamflood phase. Lower permeability at the top impedes steam override and thus assures a better conformance for the steamflood.

The opposite is true for the case where the permeability increases upward. In this case, the oil recovery in the steamflood phase is reduced to merely 37.0% OIP at the start, just as expected. The results for the two involving random ordering fall between the two extremes of systematic ordering.

Systematic ordering of permeability, increasing downward, favors the steamflood.

8. Oil and Rock Properties Comparison

To compared the actual oil and rock properties in SaBei Transition-Zone with the results of calculating and making simulation studies on steamfloodling light-oil reservoirs, and making the further studies whether or not it is suitable for steamflooding. (Table 1).
Table 2 Oil Displacement Efficiency Of Different Methods

| Tem, °C | Displacement methods | Soi, % | Sor, % | ED, % |
|--------|----------------------|--------|--------|-------|
| 50     | waterflood           | 65.2   | 28.8   | 55.8  |
| 120    | waterflood           | 65.5   | 21.0   | 68.0  |
| 200    | waterflood           | 64.9   | 19.0   | 70.7  |
| 200    | steamflood           | 65.1   | 11.9   | 81.7  |

As it is revealed in the Table 1, the conditions in SaBei oil-field is in accordance with the simulative results. And the crude-oil has the heat sensitivity also. The oil viscosity changes rapidly when the temperature changes at the point of 50°C. So all these properties will be suitable and beneficial for making steamflood.

9. Field Experiences

Since SaBei oil-field has in the stage of high-water saturation after waterflooding with the lower recovery, a large number of pilot tests have been developed for improving oil recovery. In 2005-2008, 4 producing wells had been chosen to make a 3-cycles steam soak in SaBei transition belts area. The expected effect has been obtained which increasing products in average per day amounting to 6.4t, decreasing WOR as 7.4.At the end of the July.2008, the increased output reached to 5277t.

Another thermal recovery experience was held in the area of BeiErDong in 19.Oct.2006—13.Jan.2007, which has the better oil properties than the Transitio-belts. This area applied the tri-compound displacement before steamflooding. And it is also made a success for increasing output per day as 8.6t, 634t was gained cumulatively. The oil recovery increased 10%.The two successful thermal tests indicate that steamflood thermal recovery could make the higher oil recovery no matter the timing of steamflood.

10. Simulation and Analysis for Efficiency of Steamflooding

Simulating with the actual oil sample in SaBei transition belts, and to analyze the efficiency of different displacement methods. Table 2 lists the four displacement methods: waterflood when temperatures are 50°C, 120°C, 200 °C respectively and steamflood (200°C). It comes to the conclusion that steamflood will increase the efficiency 11.0% than the same temperature waterflood and exceeding nearly 25% than waterflood as in the temperature of 50°C. The cumulative residual oil saturation decreases correspondingly with the temperature increases, and get the lowest as 11.9% when steamflood applied. There is no doubt that steamflood would decrease the SOR while at the same time increase Oil recovery.

Another simulation has also made to predict the steamflood efficiency in SaBei transition belts. As it is shown in Table 3, when the smaller well spacing was used, the total oil recovery from both waterflood and steamflood, based on the OOIP, is 32.98+17.89=50.87%, that is means steamflood applied in SaBei Transition-Zone has a veridical feasibility.

Table 3 Oil Recovery Prediction Of Different Patterns And Sizes

| Patterns and sizes | Waterflood produced-degree at present(%) | Produced degree in the stage of waterflood(%) | Waterflood oil recovery(%OOIP) | Steamflood Oil Recovery(%OOIP) | Ultimate Recovery(%OOIP) |
|--------------------|------------------------------------------|---------------------------------------------|-------------------------------|-------------------------------|--------------------------|
| 250×350 slant      | 23.81                                    | 8.1                                         | 31.91                         |                               |                          |
| 125m, invert        | 23.81                                    | 9.17                                        | 32.98                         | 17.89                         | 50.87                    |
Patterns and sizes | Waterflood produced-degree at present(%) | Produced degree in the stage of waterflood(%) | Waterflood oil recovery(%OOIP) | Steamflood Oil Recovery(%OOIP) | Ultimate Recovery(%OOIP)
--- | --- | --- | --- | --- | ---
nine-spot, square | 23.81 | 9.17 | 32.98 | 15.05 | 48.03
(125m-150m) ×195m,diamond | 23.81 | 9.10 | 32.91 | 13.45 | 46.36
150m,square | 23.81 | 9.10 | 32.91 | 13.05 | 45.96
150mdiamond | 23.81 | 9.10 | 32.91 | 13.05 | 45.96

So as it has been shown in the comprehensive simulation study of steamflooding light-oil reservoirs after waterflood, the SaBei Transition-Zone will be in accordant with the simulative results in the aspects of reservoir conditions. And the successful field experiences also proved that steamflood will be beneficial for increasing oil recovery in SaBei oil-field.

11. Conclusions

1. Steam distillation is an important recovery mechanism in light-oil steamflooding while viscosity reduction lies in the second place.
2. Two general observation are the oil recovery from steamflooding light-oil reservoirs after waterflood can reach as high as 50-60% OIP at the start of the steamflood, and reservoir oil and rock properties have critical influence on steamflood performance.
3. Below are some guidelines for selecting candidates for steamflooding after waterflood. Light-oil reservoirs with the following properties will be preferred.
   - Oil gravity >26°API [0.9 g/cm³], thickness ≥20ft [≥6.1m]; porosity ≥30%; residual oil saturation to water ≥40%; permeability >200md; and permeability variation with systematic ordering, increasing downward.
4. SaBei Transition-Zone has the favorable conditions for steamflooding which will be beneficial to increasing oil recovery. And the field experiences have been developed in SaBei Transition-Zone also proved the feasibility of steamflooding.

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