Research on influencing factors of injection capacity in cycle steam stimulation process with horizontal well in Bohai oilfield

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Abstract. Since the beginning of the 21st century, the proportion of heavy oil production has been increasing. Cycle steam stimulation (CSS in short) is the prevailing technology for the development of heavy oil reservoirs and has made a great contribution to the development of heavy oil. However, the current research on the factors affecting the steam injection capacity of CSS heavy oil reservoirs and the degree of influence of each factor is insufficient. Oil recovery and heat utilization efficiency are poor, especially in the oil fields with poor reservoir conditions and severe heterogeneity. In this paper, the reservoir geological model of the Bohai oilfield was established, and the CSS development was predicted. The problems in the development process of CSS in Bohai oilfield were pointed out. Then, laboratory experiments were carried out to study the steam absorption law of CSS heavy oil reservoirs in consideration of reservoir permeability, steam injection rate, steam injection temperature and crude oil viscosity. The result showed that higher formation permeability and steam injection temperature could improve oil displacement efficiency; higher steam injection rate would reduce oil displacement efficiency. Finally, the influence rules of different injection-production parameters were clarified to shed some lights on the efficient exploitation of heavy oil reservoirs.

1. Introduction

Among the world's oil and gas resources, heavy oil has a huge potential for exploitation and accounts for a large proportion [1]. China's current bitumen and heavy oil resources are estimated to be more than 300×10⁸t [2]. Since the beginning of the 21st century, as the current recoverable reserves of light oil reservoirs continue to decrease and the demand for oil continues to increase, the proportion of heavy oil production would continue to improve. China's offshore heavy oil resources are abundant and relatively concentrated in the Bohai Sea, with broad exploration prospects and geological reserves [3]. As of the end of 2009, CNOOC has discovered 22 heavy oil fields in the Bohai Sea, with total heavy oil reserves of 2.46 billion cubic meters, of which 1.44 billion cubic meters of proven geological reserves and 350 million cubic meters of predicted geological reserves. The reserves of heavy oil account for 70% of the discovered geological oil reserves in this area and 56% of the discovered geological reserves of heavy oil in China [4].

Cycle steam stimulation, steam flooding, in situ combustion and hot water flooding are the main methods of thermal oil recovery at present [5]. Currently, the two relatively mature and widely used heavy oil recovery technologies are cycle steam stimulation and steam flooding [6, 7]. However, the main problem that restricts the improvement of recovery percent of reserves is the occurrence of steam
channeling, which would continue to appear with the increase of steam injection volume and steam injection rate [8-10]. Heavy oil thermal recovery technology has been listed as one of the leading technologies for heavy oil recovery in the Bohai block and Bohai oilfield has completed multiple CSS tests. As it enters the stage of multi-cycle steam stimulation, affected by factors such as reservoir heterogeneity, mobility ratio and crude oil viscosity, steam channeling is serious during the heat injection process and heat cannot effectively act on the crude oil which means the heat utilization rate is low [11]. When steam channeling is severe, it may even cause production wells to be shut in, directly affecting oilfield productivity [12].

Therefore, further research on the mechanism and influencing factors of steam channeling and discussion on measures to prevent steam channeling are of great significance to improve the recovery effect of heavy oil reservoirs in the cycle steam stimulation and steam flooding stage [13]. Compared to onshore oilfields, the Bohai Sea heavy oil has a depth of 1000~1300m, well slope depth has a depth of 1300~1600m above, and the formation pressure is as high as 10MPa [14]. Although the development experience of cycle steam stimulation thermal recovery in mid-deep onshore heavy oil fields can provide a reference for the development of mid-deep heavy oil fields in the Bohai Sea, but in view of the high production and high return needs of offshore heavy oil field development, there is still a lack of systematic research on the thermal recovery mechanism and efficient development technology of medium and deep offshore heavy oil fields [15, 16]. Thus, according to the geological characteristics of the Bohai oilfield and the pilot test of steam stimulation, this paper studies the influencing factors of steam injection capacity and steam channeling of offshore heavy oil steam stimulation through indoor physical simulation experiments, reservoir numerical simulation and theoretical analysis which provide theoretical guidance and technical support for steam stimulation and thermal recovery in offshore oilfields [17-19].

2. Numerical simulation of steam channeling

In view of the uneven steam injection capacity of the actual formation during the CSS process, it causes steam to flow along the high permeability channels of the formation, thereby causing steam channeling. In order to analyze this problem in the actual production process, it is necessary to clarify the cause of uneven steam injection through numerical simulation, and verify it through physical model simulation experiments. Based on the geological characteristics of Bohai heavy oil reservoirs and related production conditions, an actual geological model was established to conduct numerical simulation research on steam channeling in horizontal wells. The actual geological model and the local infill well pattern diagram of the well are shown in Figure 1. The grid plane size is 5mx5m after local encryption.

![Figure 1. Geological simulation model of Bohai oil field](image)

According to the current development performance of the Bohai oilfield, this paper studies the reservoir development performance of the Bohai oilfield at 10 years of steam stimulation at different steam injection intensities. As shown in Figure 2 and Figure 3, it illustrates that the steam injection
intensity increases by 5 m$^3$/m with CSS for 10 cycles and the steam (water) transverse sweep radius along well A23H increases by about 5m. When the steam injection intensity is 20 m$^3$/m and the CSS is 10 cycles in the oil field, the transverse sweep radius along the horizontal well is less than 50m.

![Image](image1.png)

(a) 10m$^3$/m  (b) 15m$^3$/m  (c) 20m$^3$/m

**Figure 2.** Distribution of reservoir water saturation in Well A23H after 10 cycles of CSS with different steam injection intensities.

![Image](image2.png)

(a) 10m$^3$/m  (b) 15m$^3$/m  (c) 20m$^3$/m

**Figure 3.** Distribution of reservoir temperature in Well A23H after 10 cycles of CSS with different steam injection intensities.

By simulating the actual CSS model for 10 cycles at different steam injection intensities (10m$^3$/m, 15 m$^3$/m and 20 m$^3$/m, no increase in the cycle steam injection intensity) production, combined with the reservoir distribution of water saturation and temperature after 10 cycles, we analyze the distribution of oil and gas in the formation and get the following conclusions:

1. The higher permeability and the lower the pressure during the entire injection process, the stronger the steam injection capacity.
2. As the steam injection rate increases, the steam sweep radius increases, which is more conducive to the expansion of steam.
3. The steam injection temperature increases and the steam injection index increases, which is more conducive to steam injection.

In the model construction of numerical simulation, there is an idealized construction for the simulation of actual formation parameters and production systems, which cannot fully reflect the flow and distribution of oil and gas in real pore. Therefore, it is necessary to carry out indoor physical model experiments. The physical model experiment studies the influence of different permeability, steam injection rate and steam injection temperature on the steam injection law of horizontal wells.
3. Experiments

3.1. Experiment apparatus and materials

Three oil samples (1#, 2# and 3#) were taken from the thick oil reservoirs in the Bohai oilfield, and their viscosity temperature curves are shown in Figure 4. The water used in the experiments is deionized water and the purification device is a Millipore Elix-10 purification unit. The viscosity of heavy oil was measured by HAAKE MARS III rheometer (maximum test temperature 300°C, maximum test pressure 40 MPa). The sand samples used for filling sand-packed tube are taken from sand wells (mesh number at 40-60, 60-90 and 90-120 mesh). By controlling the proportion of different mesh sand samples, it is possible to obtain sand-packed tubes with different permeability. The experiment equipment includes water container, constant-flux pump, steam generator, intermediate container, incubator, sand-packed tube, coil pipe, pressure transducer, fluid-collection system, pressure sensor.

![Figure 4](image1.png)

**Figure 4.** Curve of viscosity vs temperature in Bohai Oilfield.

3.2. Experiments procedures

![Figure 5](image2.png)

**Figure 5.** Flow chart of steam injection device.

The apparatus of steam injection capability physical simulation experiment is shown in Figure 5, the apparatus has three main modules: reservoir model system, steam-generation driving system, and data-collection system. Pressure sensors are installed at the inlet and outlet of the sand-packed tube model to collect and record pressure data in real time. Steam injection rate can be controlled by ISCO pumps; steam injection temperature is set by steam generator; by controlling the proportion of different mesh
sand samples, it is possible to get reservoir model with different permeability; the liquid collecting device can collect the liquid at the outlet of sand-packed tube model and monitor the oil-displacement efficiency in real time.

4. Results and discussion

4.1. Influence of permeability on steam injection capacity

Permeability is one of the main physical properties of heavy oil reservoirs and it can influence steam injection capacity in the process of steam stimulation. Sample 1# oil was selected as the experimental oil with an experimental temperature of 100°C, and three levels of sand-packed tubes, 500mD, 1000mD and 3000mD, were selected to study the effect of permeability on the steam injection capacity. The results are shown in Table 1, Figure 6 and Figure 7.

Table 1 shows that as the permeability increases, the average injection pressure decreases and the steam injection index increases. And it can be seen from Figure 6 that the higher the permeability, the lower the pressure during the entire injection process. The higher the permeability, the stronger the steam injection capacity. In addition, Figure 7 illustrates that the higher the permeability, the higher the oil recovery. When the permeability is 457mD, the oil displacement efficiency is only 48%; when the permeability is 2851mD, the oil displacement efficiency is as high as 56.67%, increasing by 8.67%.

Table 1. Experimental results of injection capacity at different permeability levels (100°C)

| Permeability (mD) | Steam injection rate (mL/min) | Average pressure (MPa) | Steam injection index (mL/min MPa) | Maximum pressure (MPa) |
|-------------------|-------------------------------|------------------------|-----------------------------------|------------------------|
| 457               | 1                             | 1.184                  | 0.84                              | 7.891                  |
| 1153              | 1                             | 0.974                  | 1.03                              | 6.234                  |
| 2851              | 1                             | 0.683                  | 1.46                              | 4.698                  |

Figure 6. Curve of steam injection pressure vs permeability.
4.2. Influence of steam injection rate on steam injection capacity

Different steam injection rate can have an effect on oilfield development, so experiments are designed to study the effect of steam injection rate on steam injection capacity. Sample 1# oil was selected as the experimental oil with an experimental temperature of 200°C, and 3000mD sand-packed tube. The results of the experiments are shown in Table 2, Figure 8 and Figure 9.

Figure 8 illustrates the steam injection pressure increases with the increase of the steam injection rate, while the average steam injection index decreases with the increase of the steam injection rate. When the steam injection rate is 0.5mL/min, the maximum pressure during displacement is 1.534MPa, the average pressure is 0.285MPa, and the steam injection index is 1.75. When the steam injection rate is 2mL/min, the maximum pressure for driving 6.015MPa, the average pressure 1.242MPa, and the steam injection index is 1.75.

In addition, as the steam injection rate increases, the oil recovery decreases. When the steam injection rate is 0.5mL/min, the oil recovery is 75.24%; when the steam injection rate is 2mL/min, the oil recovery drops to 46.98%, a decrease of 28.26%.

Table 2. Experimental results of injection capacity at different Steam injection rate.

| Steam injection rate (mL/min) | Permeability (mD) | Average pressure (MPa) | Average Steam injection index (mL/(min·MPa)) | Maximum pressure (MPa) |
|-------------------------------|-------------------|------------------------|-----------------------------------------------|------------------------|
| 0.5                           | 3123              | 0.285                  | 1.75                                          | 1.534                  |
| 1                             | 3003              | 0.604                  | 1.66                                          | 3.413                  |
| 2                             | 3055              | 1.242                  | 1.61                                          | 6.015                  |

Figure 8. Curve of Steam injection pressure vs steam injection rate.
4.3. Influence of steam injection temperature on steam injection capacity

Heavy oil is very sensitive to temperature. As the temperature rises, the viscosity of heavy oil would greatly decrease. In order to study the influence of steam (hot water) temperature on injection capacity, the experiment studied the relationship between the steam injection index and the temperature at a permeability level of 1000 mD and a steam injection rate of 1 mL/min.

Table 3 shows the steam injection index increases as the steam injection temperature increases indicating that the higher the temperature, the more favorable the injection of steam. Oil recovery is positively correlated with steam injection temperature. When the temperature is 52℃, the oil recovery is 41.73%; when the injection temperature is 300℃, the oil recovery is 83.48%, and the oil recovery is improved by 41.75%.

Table 3. Experimental results of injection capacity at different temperature.

| Temperature (℃) | Permeability (mD) | Average pressure (MPa) | Steam injection index (mL/min·MPa) | Maximum pressure (MPa) |
|-----------------|-------------------|------------------------|-----------------------------------|------------------------|
| 52              | 1012              | 1.375                  | 0.73                              | 8.521                  |
| 100             | 1153              | 0.974                  | 1.03                              | 6.234                  |
| 150             | 1086              | 0.864                  | 1.16                              | 5.613                  |
| 200             | 1086              | 0.801                  | 1.25                              | 4.898                  |
| 300             | 1105              | 0.677                  | 1.48                              | 3.181                  |

Figure 9. Curve of oil recovery pressure vs steam injection rate.

Figure 10. Curve of injection pressure vs Temperature.
5. Conclusions
In this paper, a numerical geological model is established based on actual reservoir properties. The development status of CSS is predicted according to current injection and production parameters. Laboratory simulation experiments were executed and steam injection capacity and oil recovery production performance of different influencing factors were analyzed in detail. The conclusions are summarized below:

1. The reservoir would be uneven develop along the horizontal wellbore in CSS due to the influence of reservoir heterogeneity.

2. The higher the permeability, the lower the pressure during the entire injection process and the stronger the steam injection capacity. Eventually, the steam displacement efficiency enhanced. When the permeability is 457 mD, the oil displacement efficiency is only 48%; the oil displacement efficiency increases 8.67% when the permeability is 2851 mD.

3. The steam injection pressure increases with the increase of steam injection rate, while the average steam injection index decreases and the oil displacement efficiency decreases. When the steam injection rate is 0.5mL/min, the oil displacement efficiency is 75.24%; the oil displacement efficiency drops to 46.98% when the steam injection rate is 2mL/min.

4. As the steam injection temperature increases, the steam injection index increases, which is more conducive to steam injection. The higher the steam injection temperature, the higher the oil displacement efficiency. When the temperature is 52℃, the displacement efficiency is 41.73%; the displacement efficiency is 83.48% when the steam injection temperature is 300℃ increased by 41.75%.

The model and related conclusions can be used as a significance guidance theory to the field development in Bohai oilfield, CNOOC, China.

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