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Study on main controlling factors of high injection pressure in offshore heavy oil reservoir

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Abstract. High injection pressure, insufficient steam injection rate and low bottom hole dryness seriously affect the application effect of steam stimulation in offshore heavy oil reservoir. By analyzing the factors affecting the reservoir conditions of high injection pressure during huff and puff, it can be concluded that the oil viscosity increases and the permeability decreases. The grey correlation analysis shows that the contribution of unit viscosity increase to injection pressure increase is twice that of unit permeability decrease. In view of the main controlling factors, the viscosity change of crude oil was studied indoors. The results showed that: 1) The content of heavy crude oil increased, and the viscosity of crude oil increased linearly; 2) The reverse phase point of oil emulsification at reservoir temperature is 50% water cut, and the viscosity of oil-in-water emulsion will increase with the increase of water cut; 3) the higher the viscosity of asphaltene is, the stronger the viscosity is. According to the actual situation of offshore heavy oilfield, residue of heavy components and emulsification of oil-in-water is the main factor affecting steam injection.

1. Introduction

Thermal recovery is widely used in heavy oil reservoirs, among which, steam stimulation technology, due to its simple field construction and fast efficiency, is suitable for multiple types of heavy oil reservoirs, and is also the main technology for the development of heavy oil reservoirs at present [1,2]. Due to the particularity of the environment of offshore oil fields, the research on thermal recovery of heavy oil started late. Since 2008, a pilot study on thermal recovery of multi-thermal fluid and steam stimulation has been gradually carried out in Bohai bay area. In NB35-2 oil field; the pilot test of multi-thermal fluid was carried out first and successfully [3]. At present, the steam stimulation technology has only carried out the pilot test in one offshore well - CBA32H well. Due to lack of understanding of steam stimulation, problems like serious corrosion of pipe column, break-off, high pressure of steam injection, and steam channeling have occurred, but the production is still increasing obviously. In order to speed up the development of steam stimulation technology at sea, research on steam stimulation technology and field pilot test in offshore oil fields [4] were conducted, but problems such as high steam injection pressure, low well bottom dry degree and steam channeling still occurred.

The main influence of high steam injection pressure has two aspects: on the one hand, it affects the steam injection speed during the initial injection process, thus reducing the steam injection dryness [5].On the other hand, it is easy to cause steam channeling after late injection into the stratum [6].On the whole, there are many operating wells with high steam injection pressure, short production time, long idling period, high operation cost, low oil/gas ratio, poor economic efficiency and low production speed, which seriously affect the thermal recovery output of heavy oil. Therefore, it is necessary to analyze the factors influencing the high pressure of steam stimulation and injection in offshore heavy oil reservoir, overcome the controllable factors as much as possible, improve the steam injection speed and ensure the dry degree of steam in the bottom of well, so as to improve the development effect of steam stimulation in heavy oil reservoirs.

2. Study on main control factors of steam injection high pressure in an offshore oil field

Among the influencing factors of high steam injection pressure, excluding subjective factors such as injection construction, the objective factors affecting steam stimulation and steam injection pressure are formation pollution, crude oil viscosity, reservoir property, formation clay mineral content and stratum energy [7-9].

2.1 Induction of factors affecting injection pressure

The objective factors that affect the high steam injection pressure can be divided into two types. One is that the flow resistance of the reservoir fluid becomes higher due to changes in composition, emulsification, etc. The other is the change of reservoir property caused by blockage and migration, that is, the decrease of permeability K. These two parameters can be explained by the "start-up pressure gradient" of heavy oil [10, 11]. The production well is produced by controlling the flow pressure at the bottom of the well and overcoming the flow resistance of crude oil by the driving pressure difference formed by formation energy. Therefore, in the process of steam injection, the injected steam overcomes the two forces in the stratum at the same time, so that the formation can be successfully injected, as shown in Figure 1.

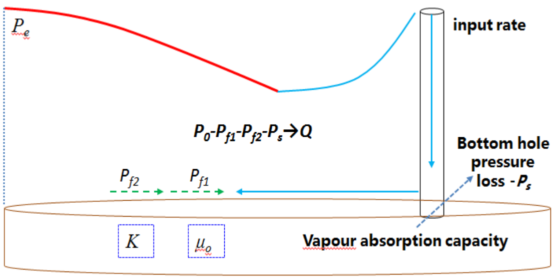


Figure 1. Diagram of reservoir stress analysis during steam injection

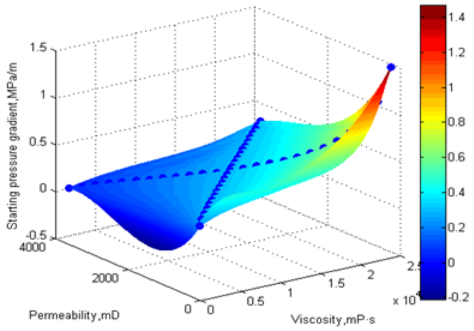
It can be seen from Figure 1 that, for the heavy oil reservoir that has its steam stimulation for the first time, formation fluid is in a dynamic equilibrium (P_{f1}-P_{f2}=P_{fw}). Pf2 is "start-up pressure", and the resistance for injecting steam to overcome is $P_{f1}+P_{f2}=2P_{f2}+P_{fw}$, which means injecting the steam into the reservoir needs to overcome the combined value of 2 times of the start-up pressure and bottom hole flowing pressure. Therefore, for the objective factors affecting steam injection, the "start-up pressure gradient" formula can be used for comprehensive analysis and judgment, and it is also suitable for multi-rotation steam stimulation wells. Based on the "start-up pressure gradient" formula, the changes in oil viscosity and reservoir permeability caused by steam injection can be fully considered.

2.2 Weight analysis of factors affecting injection pressure

From Reference literature [12] the "start-up pressure gradient" of a heavy oil reservoir in Bohai Sea was obtained, as shown in Formula 1:

$$\frac{\Delta P}{\Delta L} = 0.1237 \times \left(\frac{K}{\mu}\right)^{-1.106} \tag{1}$$

Gray relational analysis method by MATLAB software is used to analyze the fluid viscosity and permeability decline on the contribution of flow resistance. Grey correlation method is a multifactor statistical analysis method, and it describes the strength, size and order of the relationship between factors based on sample data of all the factors, and reflects the changing trend of the two factors according to the sample data. The range of the viscosity is 1,000-25,000mPa•s, and the range of the permeability is 250-3,850mD. The results are showed in Figure 2.



type	Formula 1	
	viscosity mPa·s	Permeability $1\times10^{-3}\mu m^2$
correlation coefficient	0.0134	0.0068
Contribution	66.34%	33.66%

Figure 2. Contribution of viscosity and permeability to injection pressure

As can be seen from Figure 2, the correlation coefficient of viscosity of crude oil is 0.0134, higher than 0.0068 of permeability. In addition, the viscosity of crude oil accounted for 66.34%, making up most of the contribution. In other words, each increase of fluid viscosity by 1mPa•s is equivalent to a decrease of permeability by 2mD to the starting pressure gradient. Therefore, for the offshore heavy oil field, the viscosity of crude oil in the reservoir is the main factor hindering the fluid flow and steam stimulation injection pressure.

3. Analysis of factors affecting viscosity change of crude oil

During steam stimulation, high-temperature steam not only emulsifies with crude oil [13], forming different types of emulsion, which lead to changes in oil viscosity, but also causes distillation [14]. The light component and heavy component remain in the distilled crude oil results in changes in the viscosity of the crude oil. The influence of component change and emulsification on the viscosity of crude oil in the oil field would be studied in order to guide the application of the subsequent pressure-lowering injection technology.

3.1 Influence of asphalt content on viscosity of crude oil

Deasphalting oil is obtained through separation according to industry standards. N-pentane was mixed with bituminous in different proportions (5%, 10%, 15%, 20%, 25%), and then stirred to be completely dissolved to determine the viscosity of crude oil.

The viscosity change of crude oil under different asphalt contents are shown in Figure 3:

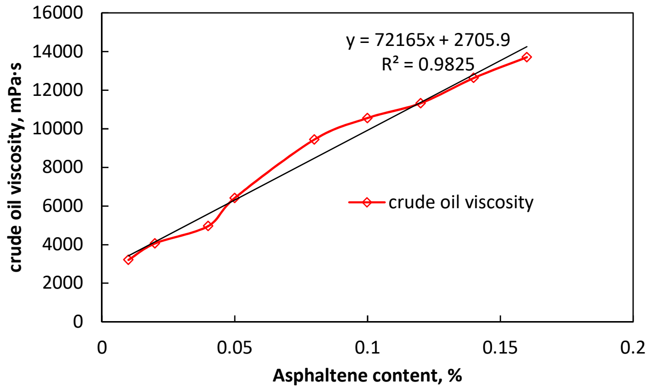


Figure 3. Changes of viscosity of crude oil with different contents of asphalt

As shown in Figure 3, the viscosity of crude oil shows an upward trend with the increase of the content of asphalt in crude oil components. By fitting the characteristic curve, it has a good linear increasing trend, and the fitting degree R is as high as 0.9825. It is consistent with the viscosity model formula of a new heavy oil component derived from literature [15], and based on this, the formula suitable for the reservoir is established, as shown in Formula 2.

$$\mu = \frac{f_a \times 10^{11.336}}{API_T^{4.792} \times T^{0.5617}} \tag{2}$$

Formula 2 is used to analyze the variation of viscosity of crude oil in the reservoir with the change of asphalt and temperature without considering emulsification of heavy oil.

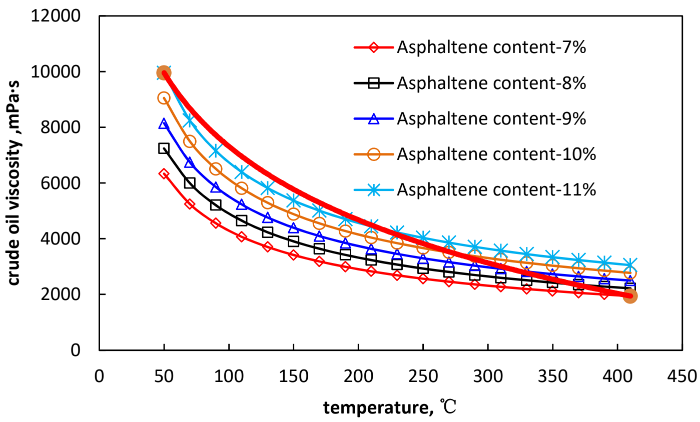


Figure 4. Viscosity changes of different bituminous contents at different temperatures

It can be seen from Figure 4 that as the steam simulation operation proceeds, light components in the stratum are distilled and the increase of heavy components such as asphalt in the remaining oil will increase the viscosity of crude oil. For each increase of heavy components by 1%, the viscosity of crude oil will increase by about 900mPa•s. With the construction of steam stimulation, the reservoir temperature gradually decreased and the crude oil viscosity gradually increased. That is to say, the regular trend of the influence of crude oil component on the crude oil viscosity during steam stimulation should be shown in the red trend line in Figure 4, showing a logarithmic upward trend. The rising range is affected by the change of the content of heavy components.

But for crude oil mixture, different components in the crude oil are in a state of relatively balance. After light component is distillation, the balance would be broken, and heavy components would precipitate/deposit [16] to achieve new dynamic equilibrium. So, the content of heavy components in the process of steam simulation is not too big. Yang Sen from China University of Geosciences [14] found in his study that after distilling the light component, asphaltene grows at only around 0.1%. Therefore, the heavy components in the crude oil system will not change much and the influence on the viscosity of the crude oil will not be obvious.

3.2 Influence of crude oil emulsification on the viscosity of crude oil

The degassed and dehydrated crude oil and formation water were mixed in accordance with (oil: water =9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8, 1:9), and the viscosity of crude oil was measured after being mixed with mechanical vibration by oscillator.

The viscosity of the emulsion at different water contents is shown in Figure 5.

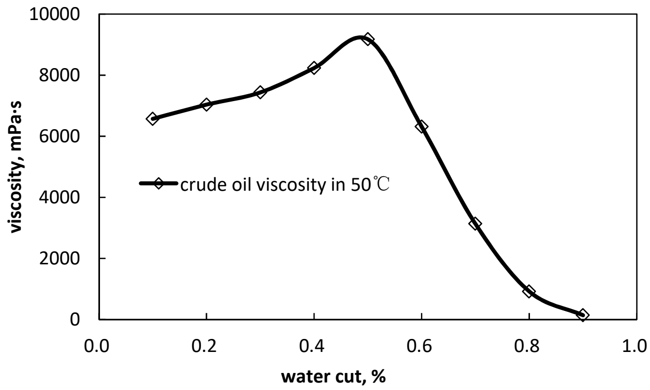


Figure 5. Viscosity of crude oil under different water content conditions

It can be seen from Figure 5 that the viscosity of crude oil increases with the increase of water content, and after reaching the reverse phase point (about 50%) [17], it decreases rapidly with the increase of water content. The analysis shows that as the water content increases, the surface of the interphase expands as the number of droplets increases, the frictional collision between particles increases, the interaction between particles increases, and the non-newtonian property of the system increases, resulting in the rise of viscosity, which reaches the maximum at the reverse phase point. Further increasing the water content, the internal structure of emulsion changes from W/O emulsion to O/W or W/O/W multiple emulsion, the shape changes into water phase and the viscosity rapidly decreases. At present, the water content of this reservoir is about 40%, which is lower than that of the reverse phase point. Therefore, the emulsion in the reservoir is mainly oil-water, and with the increase of water content, the viscosity of crude oil will further increase, hindering steam injection.

3.3 Influence of heavy component content on the effect of emulsion adhesion

Crude oil and formation water of different heavy components in 2.2 were mixed according to oil-water ratio (oil: water =8:2, 5:5, 2:8), and the viscosity of crude oil was measured. The viscosity of emulsion of different weight components is shown in Figure 6.

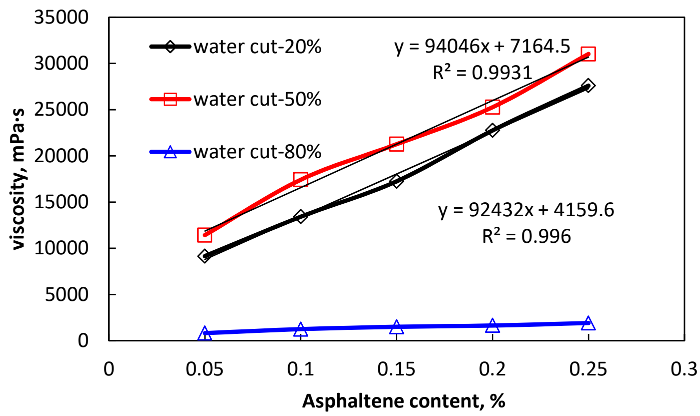


Figure 6. Viscosity of emulsion of different weight components

It can be seen from Figure 6 that the viscosity of emulsion of different heavy components is different, and the overall trend is that the viscosity of crude oil increases gradually with the increase of heavy components, and the maximum viscosity increases to 4.9 times. This is because of the aromatic and polar nature of the bituminous material. The polar functional group of the bituminous material is oriented towards the water phase, and the non-polar functional group is oriented towards the oil phase. The thing on the oil-water interface plays a role similar to surfactant. The higher the content of the bituminous material, the stronger the effect is [18].The viscosity of crude oil before the reverse phase point forms the emulsion of oil-ladled water (W/O), which has strong viscosity increasing ability. However, the influence of water-ladled oil (O/W) formed after the reverse phase point is mainly affected by the emulsification state, and the viscosity increase is not obvious. The analysis shows that the emulsion formed by water-in-oil emulsion under the condition of higher bituminous content can be more stable and larger. With the increase of water content, the viscosity of crude oil is affected more by the viscosity-increasing method than the pure asphalt content. However, as the crude oil system is covered by water phase, the increase of asphalt content has little effect on the viscosity of crude oil, showing a slight rise.

The stability of the emulsion was further analyzed, as shown in Figure 7.

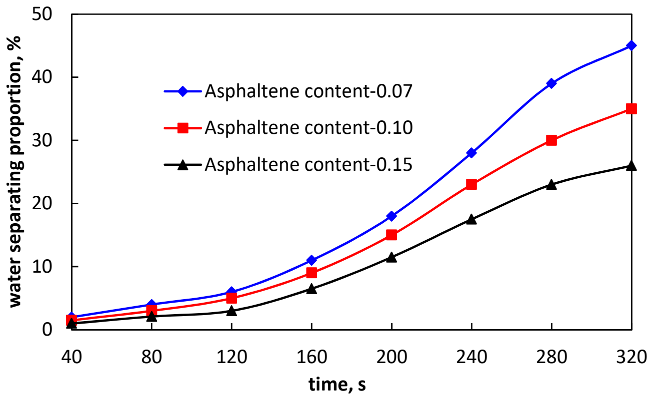


Figure 7. Water absorption of different heavy components

As can be seen from Figure 7, the higher the heavy component content of crude oil is, the better is its stability and the lower is the water yield. According to the analysis, what's stabilizing the lactescence in the asphaltene is a natural surfactant in oil, which can be absorbed on the oil-water interface to form a viscoelastic interfacial film with certain strength. The formation of this mechanically strong film prevents the merging of dispersed water droplets. Therefore, Asphalt is considered to be a natural surfactant with the strongest and most difficult capacity to stabilize emulsion [19]. Asphalt has a stabilizing effect on water-in-oil emulsion, resulting in the formation of emulsion difficult to demulsify, thus enhancing its resistance in the pore medium [20].

Therefore, the synergistic effect of crude oil composition and crude oil emulsification not only greatly increases the viscosity of crude oil, but also enhances the stability of its emulsion, making its flow resistance established in porous media more stable and hindering the steam injection, which is the main factor for the establishment of reservoir flow resistance during the heavy oil stimulation.

4. Conclusions

Through the analysis of main control factors, the contribution of fluid viscosity to flow resistance is twice as much as that of reservoir permeability, and the fluid viscosity is the main controlling factor of injection pressure rise. The maximum increase in crude oil emulsification can also reach by 1.4 times, which has a significant impact on the oil viscosity and will significantly increase the injection pressure. For every 1% increase of the heavy component in crude oil, 900mPa•s of the viscosity should be increased. However, the extraction of light components will lead to the destruction of the balance of the crude oil system, and the heavy components will separate out crude oil and enter into a new balance, so the change of the crude oil components will not increase more than 1%, and the change of crude oil components will not have a great impact on the increase of viscosity. However, the synergistic effect of changes in heavy components and emulsification can significantly increase viscosity, with the highest crude oil viscosity increasing by 4.9 times, and the stability of emulsion is also enhanced, which eventually leads to high and stable flow resistance in the reservoir.

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