The basic principle of enhancing oil recovery technology in heavy oil reservoirs

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Abstract. Due to the heterogeneity of heavy oil reservoirs and the high viscosity of heavy oil, the recovery rate of heavy oil reservoirs is much lower than that of conventional reservoirs. So increasing the recovery rate of heavy oil reservoirs is of great significance to the goal of improving the technical level of heavy oil development proposed by the National Energy Plan. This paper outlines several commonly used techniques for improving the recovery of heavy oil reservoirs, including steam flooding, hot water flooding, polymer flooding, surfactant flooding, microbial flooding, foam flooding, ultrasonic viscosity reduction technology, etc. And briefly explains the basic principles. The internal causes of the problem are analyzed, and several focal points for improving the recovery of heavy oil that should be paid attention to are put forward.

1. Introduction

With the development of conventional crude oil, its underground reserves are getting lower and lower. As a result, the huge reserves of heavy oil resources occupy an increasing proportion in the future energy structure. However, heavy oil has more residual oil after conventional water flooding and most of it is continuous and flowable. Therefore the exploiting method of these heavy oil resources has become an important topic for future research. Most of the heavy oil reservoirs in China have entered the high water cut period, and some of them have entered the extra high water cut period. The ultimate recovery rate after ordinary heavy oil water flooding is relatively low. The residual oil saturation after water flooding is high, while the oil recovery rate is low, and the effect is poor in the later stages of reservoir development. The remaining oil distribution is scattered and high in saturation, the sweep coefficient is small, the water content rise rate is fast, the water flooding recovery rate is low, and the development effect is extremely unsatisfactory. Therefore, how to further develop the remaining oil after heavy oil water flooding has become the potential to improve the development of oilfields. Because of its high content of colloid and asphaltene, heavy oil, high density, high viscosity and poor fluidity, heavy oil is difficult to exploit and requires high cost [1].

The key to improving heavy oil recovery is to reduce viscosity and friction and improve rheology [2]. Thermal recovery is the most commonly used and most successful method for heavy oil production at home and abroad currently, including steam flooding, huff and puff, hot water flooding, etc. Thermal recovery is mainly to reduce the viscosity of heavy oil by heating to improve its fluidity. In the absence of bottom water and thick oil layer, thermal recovery technology is very effective and
the recovery rate is high. However, for reservoirs with small oil layer thickness and bottom water, heat will be lost in the process of transporting and heating crude oil, and it is impossible to reduce the viscosity of heavy oil by heating. The application of thermal recovery technology in this case is limited, and it is generally considered to further improve the recovery of heavy oil reservoirs by means of cold recovery such as chemical flooding, microbial flooding and foam flooding.

2. Overview of heavy oil resources

We refer to crude oil with high asphaltene content, high colloidal content, high viscosity and high density as heavy oil. Western world collectively refers to heavy oil as heavy crude oil. Heavy oil accounts for a large proportion of the world's oil and gas resources. It is estimated that the world reserves of heavy oil, super heavy oil and natural asphalt are about \(1 \times 10^{11}\) t. Among them, China, The United States, Canada, Venezuela, The former Soviet Union and other countries have abundant heavy oil resources. The heavy oil resources and tar sand resources are about \(4000 \times 10^8\) t and \(6000 \times 10^8\) m³, and the annual output of heavy oil can reach \(1.27 \times 10^8\) t or more [3]. China usually refers to crude oil with a relative density of 0.92~0.95 and a viscosity of 100~1000 mPa*s under reservoir conditions; Crude oil with relative density of 0.95~0.98 and viscosity of 10~50 Pa*s under reservoir conditions is called extra heavy oil; A crude oil with a relative density greater than 0.98 and a viscosity greater than 50 Pa*s under reservoir conditions is called ultra heavy oil [4]. China also has abundant heavy oil and asphalt resources. At present, more than 70 heavy oil fields in 12 basins have been discovered. The total amount of heavy oil and asphalt resources is estimated to be \(300 \times 10^8\) t [5]. At present, the large heavy oil fields include Liaohe Oilfield and Tahe Oilfield [6]. Heavy oil is an important part of petroleum resources and is the primary raw material for the production of many important chemical products. It is also an important target for national oil exploration and development in recent years [7].

3. Exploiting technology of heavy oil

Since the exploitation of heavy oil in the 1960s, heavy oil exploiting technology has developed rapidly. As far as current heavy oil exploiting technology is concerned, heavy oil exploiting is dominated by thermal recovery such as steam flooding and hot water flooding, while cold recovery in Canada and Venezuela is relatively widespread [8].

3.1. Steam flooding

For high-viscosity, high-heavy and high-porosity reservoirs, steam flooding is a highly adopted method of oil recovery. China's steam flooding technology is very mature and has been widely used in many large oil fields. Steam flooding is a process in which hot steam is used as a heat carrier fluid and a driving medium to continuously inject steam into a gas injection well, thereby continuously producing oil in adjacent production wells, and using the injected heat and mass to improve oil displacement efficiency [9]. The mechanism of steam flooding includes the viscosity reduction by high temperature steam for heavy oil, the miscible driving action of steam and crude oil, and the thermal expansion of rock and fluid.

Although steam flooding is one of the most successful technical development technologies for heavy oil reservoirs [10], the heterogeneity of the reservoir and the difference in the working system of each production well result in the first steam breakthrough in the production wells with high permeability, high output and small injection-production well spacing [11]. The reservoir heat utilization rate is low, and the overall economic benefits cannot be guaranteed. At this point, the following related technical methods should be considered: (1) Reasonably adjust the amount of steam injected into the oil layer, adjust the injection volume and injection speed according to the suction capacity of the formation, and try to achieve uniform injection; (2) Intensify research on wells that are prone to gas breakthrough. In the process of steam injection, the packer can be used to seal the easy-soil porous well layer, and then the non-gas-filled well layer is selected to carry out stratified steam injection operation; (3) Mechanically or chemically seal the high-permeability layer that is prone to gas breakthrough, such as putting a hollow metal ball of appropriate size or injecting some suitable
chemical agent. (4) When performing the perforating operation, trying to avoid the high-permeability layer or other layers from being shot at the same time. It is necessary to effectively control the permeability difference in each layer for specific exploiting conditions to ensure efficient exploitation [12].

3.2. Huff and puff
Huff and puff is a method of firstly injecting a certain amount of hot steam into an oil well, and then performing soaking for a period of time, after the heat of the steam is diffused to the oil layer, and then the well is produced [13]. The application of huff and puff in China is very extensive. Most of China's heavy oil production is obtained through huff and puff technology. The principle of this technology can be summarized as: (1) The viscosity of the crude oil in the oil layer is reduced by steam, and the fluidity is enhanced; (2) The thermal expansion of rocks and fluids promotes the development of reservoirs; (3) For oil layers with higher pressure, the elastic energy of the oil layer is fully released after heating, which increases the driving force of oil displacement; (4) The high temperature steam can eliminate the pollution of the near well bore for the scouring of the rock, and it has a good plugging effect [14].

3.3. Hot water flooding
Hot water flooding is to inject hot water into the layer. After the crude oil is heated, the viscosity is greatly reduced, and the fluidity of the crude oil is significantly enhanced. At the same time, the volume of the rock and reservoir fluids expands after being heated, which reduces the residual oil saturation and promotes the wetness of the rock and prevents the formation of high-viscosity oil bands. The hot water flooding technology is easy to operate and is the same as the conventional water flooding method. The mechanism of action of hot water flooding is mainly manifested in: (1) The heat carried by the hot water can increase the temperature of the crude oil, thereby reducing the oil-water mobility ratio, and the effect on the heavy oil is obvious. In the case of constant oil saturation and relative permeability, increasing the temperature can cause the water phase to advance forward, thereby increasing the oil recovery rate when the water breaks [15]. (2) When the temperature of the reservoir crude oil increases, the residual oil saturation will be significantly reduced [16]. At the same time, an increase in the temperature of the crude oil will result in a change in the relative permeability, which is generally advantageous; (3) The fluid in the reservoir and the expansion of the rock after heating will also promote the displacement process of the crude oil.

The hot water flooding surface process is simple, has a good oil-increasing effect, and achieves an efficient development of the oil field to a certain degree. However, the extent of enhanced oil recovery by hot water flooding is relatively low, so it cannot be the dominant technology for thermal recovery. For some cases where the hot water flooding cannot significantly improve the oil recovery, it may be considered to add a suitable surfactant when injecting hot water to form an oil-in-water emulsion, thereby reducing the viscosity of the crude oil and the oil-water interfacial tension. Reducing energy consumption and efficiently improving oil recovery. At the same time, hot water flooding can also be used as a follow-up exploiting method for steam flooding or other thermal recovery methods, making full use of thermal energy, improving overall technology and improving economic efficiency.

3.4. Polymer flooding
Polymer flooding is the most widely used method for chemical flooding to enhance oil recovery. The polymer flooding is to add polymer that having a high molecular weight to the injected water, such as partially hydrolyzed polyacrylamide, polysaccharide, or the like. The polymer can increase the viscosity of the water phase to reduce the oil-to-water ratio, increase the volume of the water, and improve the recovery of crude oil [17]. Secondly, the elastic polymer solution generates viscous force through viscoelasticity and improves the oil displacement efficiency of the crude oil. Generally, polymers selected for polymer flooding should have good thermal and chemical stability. Polymer flooding also has many disadvantages. For example, most of China's oil fields are aggressive injection
type, so large pores are generated, the coefficient of formation variation increases, and the reservoir heterogeneity increases. It is easy to coagulate during polymer flooding, which greatly reduces the efficiency of oilfield development. Therefore, it is very important to conduct water shutoff and profile control before polymer flooding. In addition, the viscosity of the polymer solution is high, and the initial pressure gradient during water flooding cannot be exceeded when it is displaced, otherwise the rock structure will be destroyed [18].

3.5. Surfactant flooding
In the exploiting of heavy oil reservoirs, the surfactant flooding is to inject a suitable aqueous surfactant solution into the well to disperse the heavy oil under the emulsification of the surfactant solution and form a stable O/W emulsion, therefore greatly reducing the viscosity of the heavy oil, so that the flow capacity of heavy oil is improved. Secondly, the surfactant solution has the ability to reduce the interfacial tension and soften the interface film, so that the flow resistance of the oil droplets is reduced. The addition of a surfactant solution increases the efficiency of the oil washing, thereby increasing oil recovery.

3.6. Alkali flooding
Alkali flooding is the first chemical flooding technology to be tested in the field. However, due to the complicated oil displacement mechanism and too many restrictions, it has not been widely used in the field. The main mechanism of alkali flooding is that the alkali reacts with the acidic substances in the crude oil to form an in-situ surfactant, which reduces the oil-water interfacial tension and thus reduces the flow resistance of the crude oil [19]. The acid value of heavy oil is generally large, alkaline solution is easy to emulsify heavy oil, and can change the wettability of the reservoir, which is very beneficial for the exploitation of heavy oil [20]. However, the alkaline solution not only reacts with the crude oil, but also reacts with the rock and other formation fluids, resulting in excessive alkali consumption, alkali breakthrough and exploiting lag. Therefore, a rigorous test is required before the alkali flooding to select an alkali solution compatible with the oil field. In the process of alkali flooding, scaling is prone to occur, which has an impact on the development of the oilfield. Therefore, the choice of alkali solution concentration is also very important.

3.7. Microbial flooding
Microbial flooding is a method of directly injecting microorganisms into the stratum, using the growth and metabolism activities of microorganisms and the interaction of microbial metabolites with substances in the reservoir to increase crude oil [21]. It is an inexpensive, effective and high-tech enhanced oil recovery technology. The mechanism of microbial flooding can be divided into: (1) Microbial activity produces acidic substances that dissolve the formation rocks, thereby improving the permeability of the reservoir; (2) Microorganisms secrete metabolites with surface activity in metabolic processes under certain culture conditions, which can reduce oil-water interfacial tension and improve oil displacement efficiency; (3) Microorganisms decompose high-molecular-weight hydrocarbons in crude oil while releasing gas to enhance oil displacement; (4) The cells produce by the growth and development of the bacteria in the porous medium of the oil layer and the metabolism of the bacteria can fill the hypertonic channel of the water-injected oil layer and increase the sweep coefficient [22].

3.8. Foam flooding
As a method to improve the recovery of heavy oil reservoirs, foam flooding has carried out a large number of indoor research and field tests locally and abroad. Studies have shown that foam as a steam drive fluid control agent can effectively prevent steam breakthrough, and can prevent hot water fingering in hot water flooding, thereby increasing the volume of steam and hot water flooding. As an oil displacing agent for heavy oil reservoirs, foam can improve the adverse fluidity ratio of the displacement agent to heavy oil, increase the sweep coefficient of the displacement agent, and the
foaming agent also has the effect of improving the oil washing efficiency. Therefore, foam flooding technology has shown good development prospects both as a fluidity control agent to improve the development effect of heavy oil steam and hot water flooding, or as an oil displacing agent to improve the recovery of heavy oil reservoirs [23].

Although the foam flooding has good oil displacement characteristics, due to the bulky volume and unstable structure of the foam, the surfactant component contained in the foam is easily adsorbed by the reservoir rock mineral, resulting in a decrease in stability. However, the stability of the foam affects the survival time of the foam in the reservoir, the area of action, and whether or not gas is formed. Therefore, it is necessary to improve the stability of the foam from a technical level, thereby improving its oil displacement efficiency.

3.9. Ultrasonic viscosity reduction technology

With the rapid development of ultrasonic technology, the physical and chemical effects of ultrasonic waves have been widely concerned, and ultrasonic technology is also becoming more and more popular for reducing the viscosity of heavy oil. The viscosity reduction mechanism of ultrasonic waves is: (1) The mechanical vibration of the ultrasonic wave acts to homogenize and agitate, causing the cavitation bubble to vibrate strongly with the radiation flow and the micro-flushing flow, which weakens the tension and friction of the liquid surface. The solid-liquid interface layer is destroyed, that is, the mechanical vibration is good to reduce the surface friction of the heavy oil, thereby reducing the viscosity of the heavy oil. (2) Cavitation causes the tiny bubble nuclei in the heavy oil to collapse, and forms strong high temperature and high pressure and local impulse waves in an instant, causing the macromolecular groups such as asphalt and long-chain paraffin hydrocarbons in the heavy oil to break. At the same time, the stable disc-like aromatic ring structure in heavy oil naphthenes is destroyed, the atomic ratio of hydrogen/carbon is increased, the size of asphaltene and colloidal molecules is decreased, the content of naphthenes is decreased, and the molecular weight is significantly reduced. Thereby the viscosity of the heavy oil is reduced [24].

4. Conclusions

Under the situation of increasing global energy demand, the exploitation of heavy oil reservoirs has received more and more attention, and the residual heavy oil exploiting technology is constantly improving and innovating. However, the following aspects are still the focus of our attention.

(1) Heavy oil thermal recovery is more widely used than cold recovery, including ordinary heavy oil, super heavy oil and extra heavy oil. For the geological conditions of the oil layer, the adaptability of thermal recovery is also greater than the adaptability of cold recovery.

(2) With the continuous updating of theoretical knowledge and experimental data, heavy oil exploiting technology is constantly innovating. Each exploiting method has unique advantages and disadvantages. According to the different conditions of different reservoirs, adapt to local conditions, choose the appropriate exploiting technology, and maximize the economy and efficiency.

(3) The combination of different oil displacement methods may be more efficient than the single oil displacement, and the oil displacement experiment should be innovatively combined with the advantages of various oil displacement methods.

(4) For the microbial flooding technology that is exploring the experimental stage, the corresponding lab and field tests should be actively carried out. Under the big theme of environmental protection, this technology should be promoted as a clean and pollution-free oil production method.

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