Review of Chemical Viscosity Reduction Technology for Ordinary Heavy Oil Reservoirs based on Environmental Protection

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Abstract. With the increase of crude oil production in the world, the proportion of conventional crude oil is gradually reduced, so the recovery of heavy oil has become the development trend. Due to the characteristics of high viscosity and low fluidity of heavy oil, its exploitation difficulty is much higher than that of conventional heavy oil, which has become the main problem restricting its exploitation and utilization. In this paper, the commonly used chemical viscosity reduction technologies for heavy oil were reviewed, including emulsification viscosity reduction technology, oil-soluble viscosity reduction technology and catalytic modification viscosity reduction technology. Combined with literature and related oilfield experiments, this paper analyzed the mechanisms, advantages and disadvantages of technologies and prospected for future technology development of viscosity reduction technology.

Keywords: Heavy oil; chemical viscosity reduction technology; recovery; review.

1. Introduction

With the development of economy and society, international energy demand is increasing day by day. According to statistics [1], the growth rate of global disposable energy consumption was slowed down in 2019, with the total consumption of 13.82 billion tons of oil equivalent, of which fossil fuel consumption continues to increase, reaching 11.727 billion tons of oil equivalent, up 2.1% compared with 2018. With the development of international crude oil, the recoverable amount of conventional crude oil is becoming less and less. The proportion of heavy oil resources is increasing day by day, accounting for more than 70% of the world's residual oil resources. Therefore, how to improve the recovery of heavy oil has become the direction of petroleum energy development in the future [2].

Heavy oil refers to the crude oil with high relative molecular weight, high viscosity and high content of heavy components. The degassing viscosity is about 100~1000 mPas. According to the viscosity and density, it can be divided into ordinary heavy oil, extra heavy oil and super heavy oil, as shown in Table 1. Heavy oil belongs to non-Newtonian fluid. Under the same pressure gradient, the higher the viscosity of crude oil is, the slower the percolation speed is, and the lower the oil displacement efficiency of water flooding is. At present, the exploitation of heavy oil has entered the low efficiency stage with high water content and low recovery that the water flooding recovery has been reduced by 5%~30%. With the continuous exploitation of heavy oil, the viscosity of
heavy oil increases gradually. Therefore, reducing the viscosity of heavy oil becomes the key to improve the recovery of heavy oil resources [3].

Table 1. Heavy oil classification.

| Heavy oil | Name       | Ordinary heavy oil | Extra heavy oil | Super heavy oil (mineral pitch) |
|-----------|------------|--------------------|-----------------|---------------------------------|
| Category  | I-1        | 50~150             | 150~10000       | >50000                          |
| Viscosity (mPa.s) | >0.9200     | >0.9200            | >0.9500         | >0.9800                         |
| Relative density (g/cm³) | Low fluidity | Low fluidity | Non-fluidity | Non-fluidity                     |
| Fluidity  | Low fluidity| Low fluidity       | Non-fluidity    | Non-fluidity                     |
| Exploitation method | Water flooding | Water flooding | Thermal recovery | Thermal recovery                 |

This paper introduced the chemical viscosity reduction technology of heavy oil, its experimental research and field application. Chemical viscosity reduction technology is to add a certain concentration of chemical agent (mainly surfactant) to heavy oil reservoir to reduce the viscosity of heavy oil through chemical changes with the advantages of low cost, small energy consumption, simple operation, small consumption and quick effect, which has been widely used in major oil fields. It includes emulsification viscosity reduction technology, oil-soluble viscosity reducer technology and catalytic upgrading and viscosity reduction technology. At present, the research direction of chemical viscosity reduction technology is mainly emulsification viscosity reduction technology and oil-soluble viscosity reducer. Meanwhile, some suggestions on the development of chemical viscosity reduction technology are put forward in this paper, which have reference significance for the development of chemical viscosity reduction technology.

2. Emulsification Viscosity Reduction Technology

Emulsification viscosity reduction technology is to add a certain concentration of surfactant solution into heavy oil reservoirs reducing oil-water interfacial tension to improve the recovery of heavy oil [4-6]. After fully mixing with underground heavy oil at a certain temperature, heavy oil is dispersed in active water to form O/W emulsion [7]. The friction between the oil films in heavy oil can be changed into friction between the oil droplets with water as the external phase, so as to achieve the purpose of viscosity reduction. The key of the technology is to change the complex heavy oil problem into a simple thin oil problem to reduce energy consumption and improve production [8]. In the 1980s, the emulsification viscosity reduction technology was successfully tested in Canada, Venezuela and other countries, which proved the feasibility of this technology [9]. Zaki [10] studied the effect of the anionic surfactant sodium lignin sulfonate (SLS), non-ionic surfactant nonyl phenol diethylenetriamine formaldehyde ethoxylate (NDFE) and the mixture on the stability, dynamic viscosity, rheological property and interfacial tension of emulsion in pipeline transportation, respectively. By controlling the type and dosage of surfactants, it was known that the stability and interfacial activity of emulsion formed by mixture at the same concentration were better than that of NDFE or SLS. The reason was that there was a synergistic effect between anionic surfactant and non-ionic surfactant that anionic surfactants could improve the stability of emulsion at lower concentration and non-ionic surfactant could reduce the viscosity of heavy oil. Chen J. [11] selected a high molecular polymer viscosity reduction system to conduct reservoir mobility ratio and core water flooding simulation experiments. It was found that the viscosity of 600 mg/L agent solution reached 3.85 mPa·s at 70°C, which was 8.2 times higher than that of single water flooding.

Emulsification viscosity reduction technology is relatively simple and low cost, which has good recovery effect for thin reservoirs [12]. However, there are also the following problems in the process of its development: (1) In the exploitation of heavy oil, the underground wastewater will be produced, which is difficult to treat. (2) Emulsification viscosity reduction technology has strong selectivity for heavy oil. (3) When the temperature is higher than 60°C, the hydrogen bond between viscosity reducer and heavy components will break. Therefore, the technology is difficult to adapt to high temperature and high salinity reservoir [13].
To solve the above problems, Wang L. [14] analyzed the existing problems of cationic viscosity reducer to synthesize anionic-nonionic amphoteric surfactant, namely sodium octylphenol polyoxyethylene ether carboxylate (RJY-8) determining the compound system as 0.4% RJY-8 + 0.5% urea + 0.01% partially hydrolyzed PAM through indoor experiments with the viscosity reduction rate of 99% at 60 °C under the oil-water ratio of 6:4, which has been successfully applied to the Tahe Oilfield in China and achieved good test results.

3. Oil-Soluble Viscosity Reducer Technology
Oil-soluble viscosity reducer technology is a new technology developed on the basis of pour point depressant [15]. By adding oil-soluble viscosity reducer into the displacement medium, using the solvation of its own containing groups [16] and the similar phase solubility with heavy oil molecules, it enters into the lamellar molecules of colloid and asphaltene (mainly acting on the hydrogen bond), so as to modify its structure and properties, breaking its internal three-dimensional structure, destroying its internal order and cohesion, and inhibiting the aggregation of colloid and asphaltene to achieve the purpose of viscosity reduction [17]. Oil-soluble viscosity reducer technology can avoid the demulsification and dehydration problems existing in emulsification viscosity reduction technology, and has a good development prospect. However, in the process of development, there are also some problems, such as low viscosity reduction rate, high unit price, large consumption, resulting in high cost, strong selectivity and failure to meet the production requirements of single use. At present, the main research direction is to improve the viscosity reduction rate of heavy oil and reduce the impact on downstream processing [18].

To solve the problems of strong selectivity, unstable viscosity reduction effect and narrow application range of oil-soluble viscosity reducer, Chen L. [19] adopted the quaternary copolymerization system, selecting 2-acrylamido-2-methylpropanesulfonic acid (AMPS), long-chain methacrylate, styrene and acrylic acid with the molar ratio of 1:10:6:5 at 70 °C for 6 h to synthesize the sulfonate anionic oil-soluble viscosity reducer in laboratory. Guo J. [20] synthesized an oil-soluble viscosity reducer with 2-acrylic acid docosylester, maleic anhydride and styrene at the molar ratio of 3:2:2 in the laboratory. The viscosity reduction rate of the viscosity reducer could reach 95.5% at 50 °C.

4. Catalytic Upgrading and Viscosity Reduction Technology

4.1 Catalytic Hydrothermal Cracking Upgrading and Viscosity Reduction Technology
Hydrothermal cracking is a chemical reaction in which the heavy oil in the formation contacts with water at high temperature and causes cracking of a substance. In the 1990s, American scholar Clark [21] proposed that hydrothermal cracking upgrading and viscosity reduction technology was to fracture the C-S bond in heavy oil under the catalysis of metal ions and the high temperature of steam. The specific reaction mechanism was shown in the following equation:

$$RCH_2CH_2SCCH_3 + 2H_2O \rightarrow RCH_2 + CO_2 + H_2 + H_2S + CH_4$$

To further clarify the viscosity reduction mechanism of catalytic hydrothermal cracking upgrading and viscosity reduction technology, Chen E. [22] selected the heavy oil produced by Huanxiling oil production plant of Liaohe Oilfield as the research object, using (NH₄)₆Mo₇O₂₄.4H₂O as catalyst and controlling the mass ratio of colloid to water of 3:1 to react at 240 °C for 24 h. The colloid degradation rate was increased from 10.8% to more than 40%. Meanwhile, the researchers analyzed the light components in the colloid cracking products by gas chromatography, proposing that the bridge bonds between polycyclic aromatic hydrocarbons and the cleavage of β C-C bonds in the aliphatic units connected with them were also broken, and the latter was the main reason of colloid degradation. Wu C. [23] synthesized organic molybdenum catalyst and carried out the experiment of catalytic hydrothermal cracking under the oil-water ratio 7:3. The result showed that the viscosity of heavy oil reduced from 524.5 Pa·s to 14.95 Pa·s, and the viscosity reduction rate was as high as 97.15%.
The most important feature of the technology is that the hydrogen is transferred from water phase to oil phase to desulphurize and hydrogenate with sulfur-containing organic compounds in oil phase, which improves the quality of heavy oil \[24\]. The development potential of this technology is great, but it brings corresponding difficulties to the exploitation of heavy oil and subsequent treatment due to its high reaction temperature and difficult operation.

4.2 Catalytic Hydro Upgrading and Viscosity Reduction Technology

Catalytic hydro upgrading and viscosity reduction technology is a new technology combining thermal flooding technology with catalytic hydrogenation technology \[25\]. At the high temperature and under the action of catalyst, heavy oil macromolecules are hydrogenated and cracked by injecting hydrogen or hydrogen donor into the well, and the condensation reaction of heavy oil is inhibited \[26\]. The hydrocarbon ratio of the product is reduced to make the product light, thus realizing viscosity reduction of heavy oil. Compared with the above ground upgrading technology, the underground catalytic hydro upgrading technology does not need large-scale ground heating equipment. However, due to the problems such as poor catalyst effect, lack of sufficient hydrogen donor and insufficient contact between catalyst and heavy oil, the technology is still in the laboratory research stage.

Li Y. \[27\] prepared bifunctional Ni, Pd and Ni-Pd alloy nanocrystalline catalysts by liquid-phase reduction method, using hydrazine hydrate (N\(_2\)H\(_4\).H\(_2\)O) as hydrogen donor to study the catalytic hydrogenation modification and viscosity reduction of heavy oil in Nanpu oilfield. Under the best experimental conditions, Ni-Pd alloy nanocrystalline catalyst could decrease the viscosity of heavy oil from 2688 mPa.s to 235 mPa.s with the viscosity reduction rate of 91.3%. To explore the feasibility of catalyst and hydrogen donor, the following analysis were carried out: TEM and XRD characterization of catalyst and thermodynamic analysis of hydrogen donor. The results showed that the catalyst had small particle size and uniform distribution, so it could fully contact with heavy oil macromolecules. Moreover, N\(_2\)H\(_4\).H\(_2\)O could decompose into H\(_2\) and N\(_2\) at high temperature. H\(_2\) was used for heavy oil hydrocracking, and N\(_2\) could increase formation pressure and improve heavy oil fluidity.

Cheng L. \[28\] synthesized oleic acid molybdenum catalyst and used tetrahydronaphthalene as the hydrogen donor to carry out experimental research on catalytic hydrogenation upgrading and viscosity reduction of heavy oil in Karamay Oilfield. The viscosity reduction rate of heavy oil could reach 65.87% at 240°C with the catalyst dosage of 0.8wt% and the tetrahydronaphthalene dosage of 1.5ml. To explore the reasons of upgrading and viscosity reduction of heavy oil, the researchers carried out four component content analysis, pyrolysis gas analysis, oil sample analysis and infrared spectrum analysis. The results showed that the content of heavy components such as colloid and asphaltene was decreased gradually, while the content of light components such as saturated and aromatic components was increased gradually. The reason was that the C-O bond, C-S bond and C-N bond were broken with the heavy oil macromolecules broken into small molecules, and the long chain broken into short chains, which realized the permanent viscosity reduction.

5. Conclusions and Suggestions

Chemical viscosity reduction technology of heavy oil involves many fields and disciplines, which has been paid more and more attention and has been applied in major oilfields all over the world, mainly emulsification viscosity reduction technology, oil-soluble viscosity reducer technology and catalytic upgraging and viscosity reduction technology. Emulsification viscosity reduction technology has low cost and good recovery effect, but there are problems such as subsequent sewage treatment and emulsion stability breaking. While oil-soluble viscosity reducer technology overcomes the problem of emulsification viscosity reduction, but it has high cost and strong selectivity for heavy oil. Catalytic upgrading and viscosity reduction technology can improve the quality of heavy oil with great development potential. But it is difficult to screen the catalyst types and recover it later.
In today's energy shortage situation, the existing heavy oil viscosity reduction technology is constantly improving and innovating. Looking forward to the future, the following suggestions are put forward: (1) In the development of heavy oil viscosity reduction technology, there are few theoretical studies on it, resulting in the unclear action mechanism of emerging technologies. So it is necessary to continuously strengthen the research of mechanism. (2) Each viscosity reduction technology has its development limitations, and heavy oil produced by single viscosity reduction technology can hardly meet the requirements of both exploitation and transportation. Strengthening the research and optimization of composite technology has become a major trend in the future, such as the combination of emulsification viscosity reduction technology and catalytic water thermal cracking viscosity reduction technology. (3) Strengthen the efforts to explore the relationship between the structure and properties of heavy oil from the micro perspective. Combining with relevant knowledge to deeply study the internal mechanism of heavy oil by the physical model and numerical simulation technology to establish a low-cost viscosity reduction system suitable for heavy oil in major oilfields.

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