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Experimental Studies on Viscosity Reduction of Heavy Crude Oil by Ultrasonic Irradiation

Qiang Hua*

Puyang Institute of Technology, Henan University, Puyang, 457000 China

**e-mail: huaqiangupc@163.com*

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Abstract—Viscosity reduction is one of the key issues for heavy oil reservoir development and its transportation. Up to now, the mechanisms for ultrasonic viscosity reduction still remain unclear, especially for that of heavy crude oil which needs to be studied urgently. Parameters have been studied on the effect of viscosity reduction. The parameters for viscosity reduction were optimized to achieve the excellent result of viscosity reduction. Experiments show that ultrasonic irradiation leads to a substantial decrease up to 86% of the viscosity of heavy oil. As for heavy crude oil, the parameters influencing viscosity reduction are in the order of ultrasonic power output, treatment time, water cut and temperature. Ultrasonic wave has an obvious influence on quantity, magnitude, and distribution of paraffin crystals. This proves the existence of synergistic effect between ultrasonic irradiation and viscosity depressant. Ultrasonic wave has an apparent effect on viscosity reduction of heavy oil.

Keywords: heavy crude oil, viscosity reduction, ultrasonic irradiation, paraffin crystals, cavitation

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INTRODUCTION

Because of more heavier component, poor flow properties and high viscosity of heavy oil, many problems have appeared in production and transportation of heavy oil. Various conventional techniques such as heating and use of viscosity depressant can be used to decrease viscosity. However, these means are not always suitable, primarily because of the drawback of large cost and low efficiency.

There is a renewed interest in the effect of ultrasonic wave on heavy crude oil in both academic studies and petroleum industry [1, 2], mainly as a result of the demand for clean, effective and economical method in viscosity reduction of heavy oil. The viscosity reduction of heavy oil is also an important environmental concern in petroleum industry. Ultrasound can decrease viscosity of heavy oil, production wells trend to yield more after ultrasonic irradiation. Ultrasonic waves can decrease the interfacial forces between oil and water [3] and they can enhance the oil recovery [4–6], which has been already applied in treatment of petroleum-contaminated soils [7–9]. Although ultrasound has a certain attenuation in propagation [10–12], it does not affect the near well treatment effect of the oil well [13]. In addition, ultrasonic irradiation becomes more popular owing to its non-contamination to environment.

Most studies have focused on the effects of different parameters of ultrasound [14], including ultrasonic frequency, ultrasonic power and treatment time on viscosity reduction of heavy oil in the transportation process. The influence of ultrasound on the quantity, magnitude, distribution of paraffin crystals and component change of heavy crude oil has not been investigated yet. In this work, experiments have been carried out to study the effects of ultrasound on quantity, magnitude and distribution of paraffin crystals.

1. DIRECT EXPERIMENT OF ULTRASONIC VISCOSITY REDUCTION

Preparing direct experimental studies is really a complex process, in which many individual parameters might be taken into account, such as ultrasonic frequency, ultrasonic power, treatment time, water cut of heavy crude oil and treatment temperature. Failure to control these parameters might lead to false conclusions. Individual parameters of ultrasound and heavy oil have different influences on the effect of viscosity reduction. In the direct experiment of ultrasonic viscosity reduction, parameter range can be calculated to evaluate the affection degree of individual parameters of ultrasound and heavy oil.

1.1. Experiment Method

The schematic diagram of the experimental apparatus is shown in Fig. 1. Experimental apparatus includes Brookfield DV-III programmable rheome-

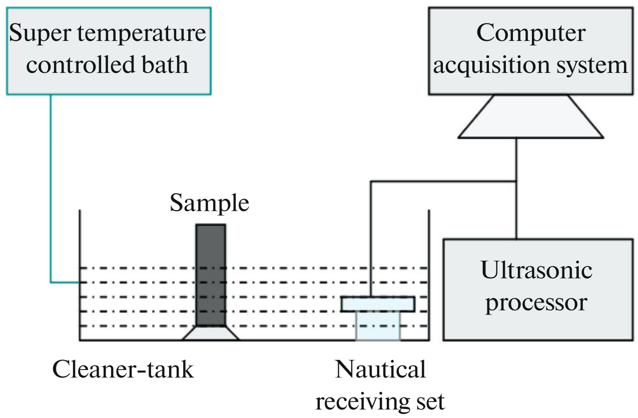

Fig. 1. Schematic diagram of experimental apparatus.

ter, super temperature controlled bath (CS601) with the dimensions 30 × 50 × 30 cm, ultrasonic processor and computer acquisition system. The nautical receiving set is an energy conversion device, and its function is to convert the input electric power into ultrasonic wave. Therefore it serves as a ultrasonic source. In this study, an ultrasonic generator (Genesis XG-500-6, CREST) was used to supply the ultrasonic waves of frequency 20 kHz and power (50, 100, 150 W) to a water bath. The viscosity of the fluids was determined by using Brookfield DV-III programmable rheometer at different temperatures.

The test samples involved in the experiments were heavy crude oil from Shengli Petroleum Administrative Bureau. In order to achieve the goal, firstly, heavy crude oil were prepared at different water cut and it were made sure they were at a certain temperature by means of super temperature controlled bath. After that, the ultrasonic processor was started to irradiate test samples at different time intervals and power outputs, then their viscosity were measured through Brookfield DV-III programmable rheometer and viscosity reduction was calculate. In addition, the experiments were repeated three times in order to check for repeatability.

It has long been known that the parameters which have apparent affection on viscosity of heavy crude oil usually contains temperature, ultrasonic power, treatment time, water cut of produced liquid and so on. Direct experiments were carried out so as to evaluate the relative influence of individual parameters of ultrasound and heavy oil. Treatment time was chosen of 3 level (5, 15 and 30 min), for viscosity reduction no longer increases over 30 min. Treatment temperature was chosen of 313.15, 333.15 and 353.15 K, considering the realistic treatment temperature in transportation of oilfields in China, with ultrasonic power at 50, 100 and 150 W in consideration of the limit of ultrasonic processor. The water cut in the direct experiment was chosen 10, 30 and 50%.

1.2. Discussion of Direct Experiment

In the direct experiments, parameter range was determined and it also stands for relative influence of individual parameters of ultrasound and heavy oil on viscosity reduction. It is evident that for oil samples considered in this study, exposure to ultrasonic waves of varying ultrasonic frequency, ultrasonic power output, water cut and treatment temperature has an effect on viscosity reduction, as shown in Table.

Through the direct experiments, the maximum reduction of viscosity occurred in ultrasonic irradiation time of 15 min, temperature of 313.15 K, ultrasonic power output of 150 W and water cut of 50% by volume. Viscosity reduction can run up to 86% with combination of these parameters.

Ultrasonic wave has a significant effect on viscosity of heavy oil due to cavitation, mechanical effect and thermal effect [7]. In the process of viscosity reduction of crude oil, ultrasound with a certain combination of parameters can stimulate minute bubbles to move, expand extremely, and then contract and finally vanish, as a result, it gives birth to extremely high temperature and pressure when numerous cavitation bubbles collapse [8]. Ultrasonic waves have an effective role in cracking and lightening of the examined heavy fuel oil which decrease its viscosity and improve its flow properties. Thermal effect is generated by boundary friction and the temperature around rises up rapidly because of higher absorption coefficient of heavy crude oil than that of light hydrocarbon. Rise in the temperature by exposure to ultrasound were easily observed in experiments. Temperature of oil samples under ultrasonic irradiation can increase by 288.15 K and pour point can decrease from 318.15 K before irradiation to 310.15 K after irradiation.

2. THE INFLUENCE OF ULTRASOUND ON PARAFFIN CRYSTALS AND COMPONENT

In these experiments, it was investigated that ultrasonic irradiation had a definite influence on paraffinic behavior. Ultrasonic irradiation not only made it more difficult for paraffin crystals to be distributed in structure of laminarization or corrugation, but also decreased the size of paraffin crystals, and augmented its quantity to result in viscosity reduction of heavy crude oil.

The paraffin crystals morphology under ultrasonic irradiation of different parameters was observed with the scanning electron microscopy. Figure 2a shows the configuration of paraffin crystals without any ultrasonic irradiation and Fig. 2b shows the configuration of paraffin crystals after ultrasonic irradiation.

The samples of dehydrated heavy crude oil were exposed to 30 min ultrasonic irradiation at the power output of 150 W at 298.15 K, and the scanning electron microscopy was used to investigate the influence of ultrasound on paraffin crystals morphology of dehy-

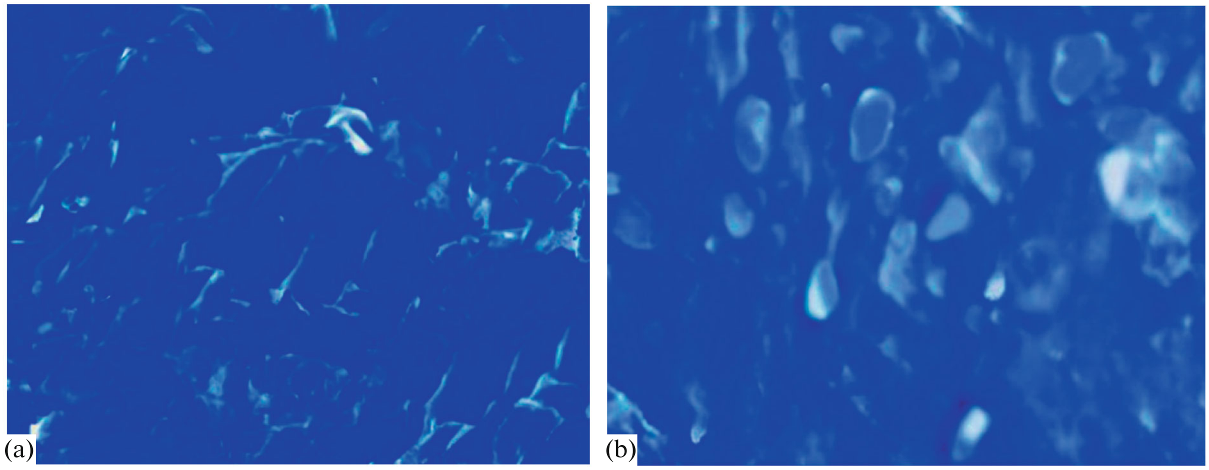

Fig. 2. Comparison of paraffin crystals pre and post ultrasonic irradiation: (a)—non ultrasonic irradiation, (b)—after ultrasonic irradiation.

drated heavy crude oil in order to analyze affection of ultrasonic wave on paraffin crystals in heavy oil.

As illustrated in Fig. 2, ultrasonic irradiation caused a change in the configuration of paraffin crystals compared with samples without any ultrasonic irradiation. For non-irradiated samples at Fig. 2a, the majority of paraffin crystals present in disorder folding of leaflet while the minority of them exist in the form of independent large flakes. In this occasion, most paraffin crystals are closely ranged in disorder and constitute three dimensional net structure, in which macromolecules are usually encircled. Asphalt molecules and jelly molecules around are restrained in the three dimensional net structure which also restrains the movement of light component. At 298.15 K the structure has a preferable stability to make heavy crude oil flows poorly at low temperatures as result of its high viscosity. But for oil samples exposed to 30 min ultrasonic irradiation at the power output of 150 W at 298.15 K, paraffin crystals gradually get rid of the restrain due to mechanic effect and cavitation, transferring from the arrangement of parafoliate in layers to that of ellipsoid of different sizes unhomogeneously distributed in heavy oil.

The change of arrangement and shape results in viscosity reduction of heavy oil, furthermore, jelly molecules between paraffin crystals can inhibit further accumulation of paraffin crystals due to the affection of van der Waals force, so the viscosity of heavy crude oil no longer rise up in extended time.

Different ultrasonic power output has conspicuous influence on quantity and size of paraffin crystals. Figure 3a depicts the configuration of paraffin crystals oil samples exposed to ultrasonic irradiation at the power output of 50 W and Fig. 3b shows the configuration of paraffin crystals oil samples exposed to ultrasonic irradiation at a larger power output of 150 W. As illustrated in Fig. 3, when exposed to ultrasonic irradiation with a small power output, paraffin crystals present in a small quantity, have large size and the shape of ellipsoid, and they assemble densely in certain areas and are distributed at a poor rate of divergence. When the power output increases from 50 to 150 W, it is easy to find the increase of quantity and decrease of particle size of paraffin crystals. Compared with the distribution of assembly at 50 W, paraffin crystals are distributed more dispersedly when exposed to ultrasonic irradiation at a larger power output of 150 W. In addition, viscosity reduction rises by 15.9%. From the results, when the ultrasonic power output increases from 50 to 150 W, this figure shows that the size of paraffin crystals at 50 W is higher than the one irradiated by ultrasound at 150 W. It can be concluded that the viscosity change in this experiment is attributed to the change of size, shape and distribution of paraffin crystals by ultrasonic irradiation in the heavy crude oil.

For dehydrated heavy oil, the majority of paraffin crystals present in disorder folding of leaflet while the minority of them exist in the form of independent large flakes. In this occasion, most paraffin crystals constitute three dimensional net structure, which has a preferable stability to make heavy crude oil flows poorly at low temperatures as result of its high viscosity. As to heavy crude oil, the influences of ultrasonic wave on paraffin crystals are clearly different for different time intervals. As illustrated in Fig. 4a, for heavy crude oil irradiated by ultrasonic wave at the water cut of 20%, paraffin crystals still present in a small quantity, and have large size and the shape of ellipsoid. They assemble densely in certain areas and are distributed at a poor rate of divergence. Some of the paraffin crystals are in the shape of sliver which should be intermediately transient state from ellipsoid to globular shape. When oil samples at the water cut of 60% are irradiated by ultrasound, paraffin crystals no longer assemble densely in certain areas, and they are more

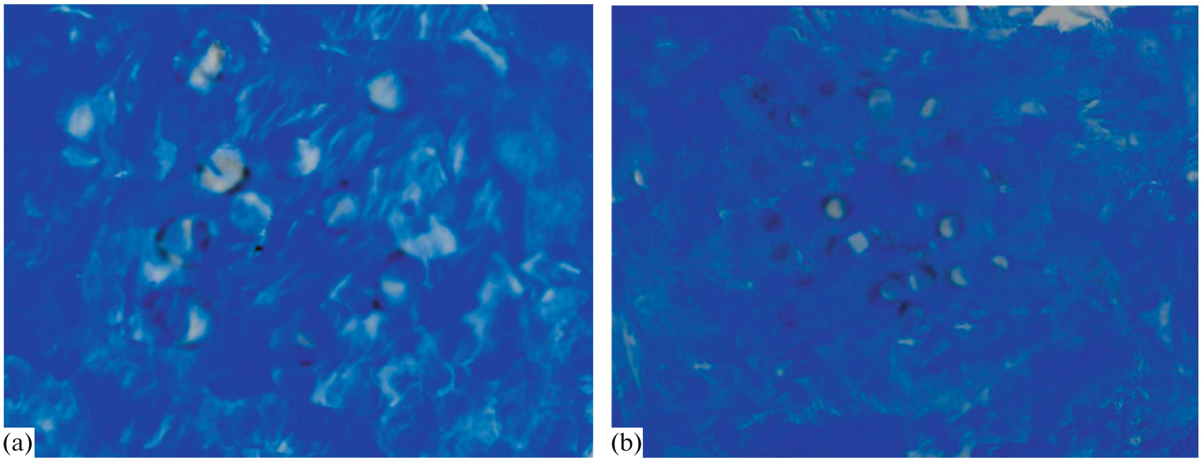

Fig. 3. Comparison of paraffin crystals at different ultrasonic power output: (a) 50, (b) 150 W.

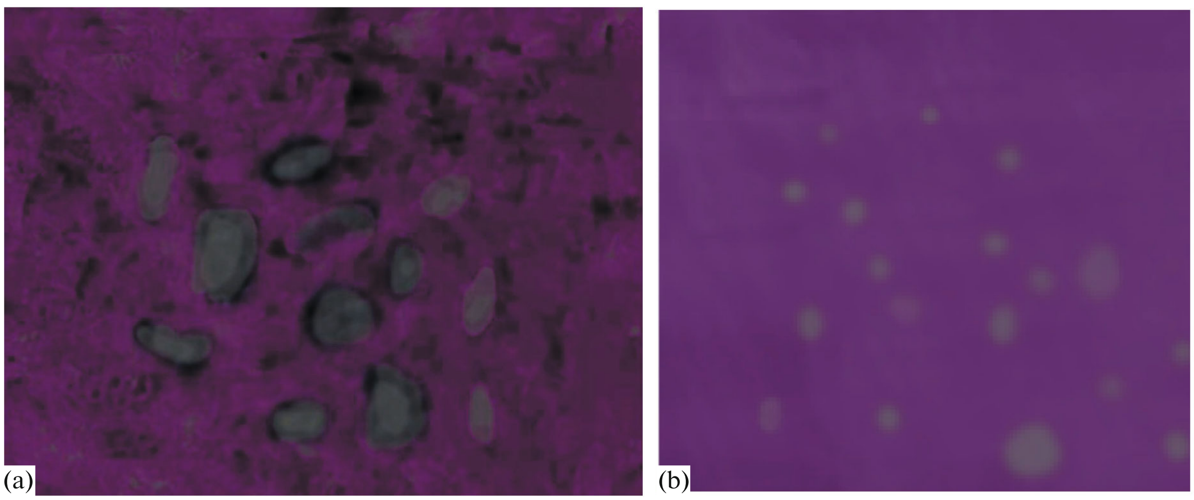

Fig. 4. Comparison of paraffin crystals under irradiation at different water cut: (a) 20, (b) 60%.

evenly distributed in heavy oil, with a big quantity and a small size in globular shape, the shape of ellipsoid vanishes and that of sliver also decreases to a large extent. When the water cut increases from 20 to 60%, this figure shows that the size of paraffin crystals at water cut of 20% is higher than the one irradiated by ultrasound at water cut of 60%.The viscosity decreases greatly and this improves the flow ability of heavy crude oil.

At present, water cut in most of the oil fields in China universally exceeds 80–90%, which lies in the favorable water cut range and the viscosity of heavy oil can decrease largely when irradiated by ultrasound.

Ultrasonic waves have an effective role in cracking and lightening of the examined heavy fuel oil. These effects decrease oil's viscosity and improve oil's flow properties. All the effects above mentioned such as cavitation, mechanical effect and thermal effect promote the emulsion of heavy crude oil. When its water cut rises to revolution point, emulsion type can be transferred from W/O to O/W, here W/O represents water-in-oil emulsion, while O/W represents oil-in-water emulsion and then the friction between molecules of heavy crude oil also changes to friction between water molecules so that there is a swift reduction of its viscosity.

3. EXPERIMENTAL STUDIES OF VISCOSITY REDUCTION BY SONOCHEMISTRY

Both ultrasonic wave and viscosity depressant can reduce the viscosity of heavy crude oil. A series of experiments were carried out to investigate the influence of combination of ultrasonic wave and viscosity depressant on viscosity reduction and to verify the synergistic effect of them.

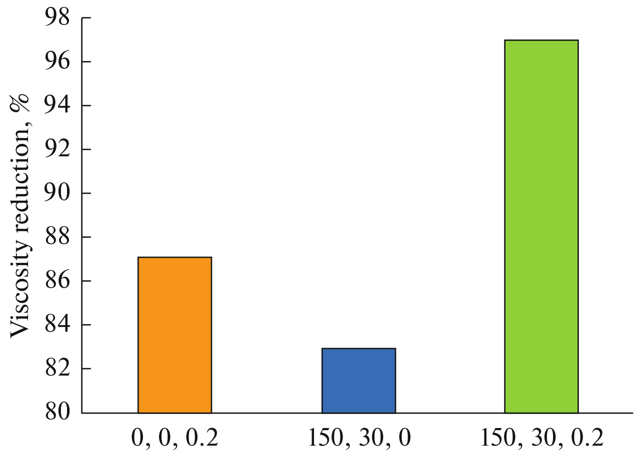

Fig. 5. Comparison of viscosity reduction of viscosity depressant, ultrasonic and sonochemistry.

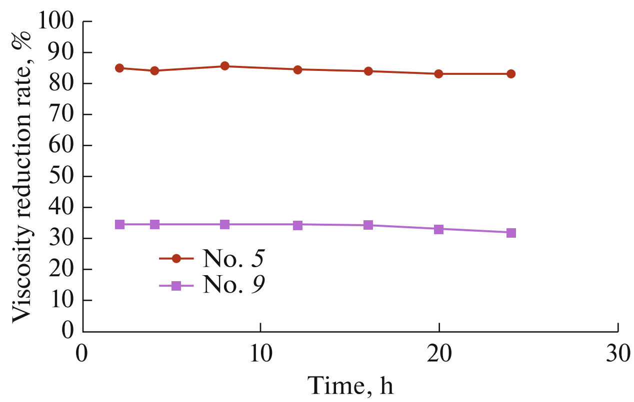

Fig. 6. Relationship between viscosity reduction and time after ultrasonic action.

Let (0, 0, 0.2) stands for the experiment about oil samples with viscosity depressant concentration of 0.2 vol %, while (150, 30, 0) stands for the experiment about oil samples under 15 min ultrasonic irradiation at ultrasonic power output of 150 W, and (150, 30, 0.2) stands for the experiment about oil samples with combination of 15 min ultrasonic irradiation at ultrasonic power output of 150 W and viscosity depressant concentration of 0.2 vol %.

Figure 5 depicts that the viscosity reduction of (150, 30, 0), (0, 0, 0.2) and (150, 30, 0.2) is 83, 87, 96.9% respectively. The experimental result of (150, 30, 0) and (150, 30, 0.2) shows about 13.9% difference with the influence of viscosity depressant, thus, it shows the combination of ultrasonic wave and viscosity depressant has a greater effect on viscosity reduction of heavy crude oil. The irradiation of ultrasonic waves alone can still reduce its viscosity but to a lesser extent compared with the influence of combination of ultrasonic wave and viscosity depressant. It also shows nearly 10% difference between (0, 0, 0.2) and (150, 30, 0.2) with the influence of ultrasound which means the combination of ultrasonic wave and viscosity depressant has a greater effect on viscosity reduction of heavy crude oil and the addition of viscosity depressant alone can still reduce its viscosity but to a lesser extent compared with the influence of combination of ultrasonic wave and viscosity depressant.

The results indicates the combination of ultrasonic irradiation with viscosity depressant can lead to intensified decrease of viscosity of heavy crude oil and the synergistic effect of them is verified. The results can be attributed to the high rate of divergence of viscosity depressant in heavy crude oil by ultrasound and this effect augments contact areas of viscosity depressant and molecules of heavy crude oil.

4. EXPERIMENTS ON THE RECOVERY OF HEAVY OIL VISCOSITY AFTER ULTRASONIC TREATMENT

It would be useful to indicate the time of relaxation for the viscosity reduction under ultrasonic treatment. In the study, two groups of experiments have been carried out to study the recovery of oil viscosity after ultrasonic treatment. Processing parameters are the same as no. *5* and *9* in Table. It is found that after ultrasonic treatment, the viscosity of heavy oil has no

Table 1. Direct array

No.	Water cut, %	Time, min	Temperature, K	Power, W	Viscosity reduction, %
1	10	5	313.15	50	0
2	10	15	333.15	100	12.7
3	10	30	353.15	150	63.2
4	30	15	353.15	50	4.3
5	30	30	313.15	100	35.1
6	30	5	333.15	150	10.6
7	50	30	333.15	50	27.5
8	50	5	353.15	100	18.1
9	50	15	313.15	150	86

obvious change, and the viscosity of heavy oil is only slightly recovered after 24 hours, and the viscosity recovery is not more than 5%, which indicates that ultrasonic treatment has no recoverability to the viscosity of heavy oil, which is beneficial to the ultrasonic treatment of heavy oil near well zone.

CONCLUSIONS

Ultrasonic wave has a significant effect on viscosity of heavy oil due to cavitation, mechanical effect and thermal effect. Ultrasound parameters should be selected properly according to actual behavior of heavy crude oil in order to get perfect viscosity reduction.

Through the direct experiments, the maximum reduction of viscosity occurred in ultrasonic irradiation time of 15 min, temperature of 313.15 K, ultrasonic power output of 150 W and water cut of 50% by volume; viscosity reduction can run up to 86.0% with combination of these parameters.

In these experiments, it was investigated that ultrasonic irradiation has a definite influence on paraffinic behavior, such as the quantity, the size and assembly feature. At present, water cut in most of oil fields in China universally exceed 80–90%, which lies in the favorable water cut range and viscosity of heavy oil can decrease largely when irradiated by ultrasound.

The results indicates the combination of ultrasonic irradiation with viscosity depressant can lead to intensified decrease of viscosity of heavy crude oil and the synergistic effect of them is verified. It is found that after ultrasonic treatment, the viscosity of heavy oil has no obvious change, and ultrasonic treatment has no recoverability to the viscosity of heavy oil.

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