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Research Article

Experimental Study on Fe_3O_4 Nanoparticle-Assisted Microwave Enhancing Heavy Oil

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Nanoparticle-assisted microwave heating of heavy oil has the advantages of fast temperature rise and high thermal efficiency. Compared with traditional heating methods, it can reduce viscosity in a shorter time. In addition, the heavy components in the heavy oil are cracked into light components at high temperatures (this high temperature cannot be reached by conventional heating methods). This process is irreversible and avoids the problem of viscosity recovery of heavy oil after the temperature is reduced. Through absorbing microwave heating experiments, study the effect of nanoparticles on the improvement of the ability of heavy oil to absorb waves and raise temperature; through the heavy oil upgrading experiment and the four-component analysis experiment, the effect of adding hydrogen donor to assist microwave on the viscosity reduction of heavy oil upgrading by nanoparticles was studied, and the problem of viscosity recovery was determined; Through the gravity drainage experiment, the mechanism of nanoparticle-assisted microwave to improve the recovery of heavy oil is studied, and the influence of water content, nanocatalyst, and microwave power on the production of drainage is analyzed. The results show that nanoparticles can improve the wave absorption and heating capacity of heavy oil, and adding 0.6 wt% of nanomagnetic iron oxide catalyst can increase the heating rate of heavy oil in microwave by 60.6%; nanoparticle-assisted microwave heating method can effectively upgrade heavy oil and reduce viscosity. The experimental conditions are 2 wt% tetralin mass concentration, 0.5 wt% nano-Fe_3O_4 particle mass concentration, microwave heating time 50-60 min, and microwave power 539 W. Under this experimental condition, the viscosity is reduced by 40%. This method has viscosity recovery problems, but final viscosity reduction effect is still very significant. Obtaining the mechanism of nanoparticle-assisted microwave to enhance oil recovery, one of which is that nanoparticles improve the wave absorption and heating capacity of heavy oil and increase the heating speed of heavy oil; the second is that the nanoparticles form local high temperature under the action of microwave, which catalyzes the hydrocracking reaction between the heavy components in the heavy oil and the hydrogen donor, upgrading and reducing the viscosity of the heavy oil, and accelerating the production of heavy oil.

1. Introduction

With the depletion of conventional oil, the world's population continues to grow, and the world's industrialization and motorization levels increase, and how to meet energy supply and demand has become a huge challenge facing the world. The world has huge reserves of heavy oil, and Venezuela, Canada, the United States, Brazil, Mexico, China, Russia, and the Middle East have large amounts of heavy oil. According to the report of the International Energy Agency, the world's total oil reserves are about 9-13 trillion barrels, and heavy oil and ultraheavy oil account for 40% of the world's oil reserves, about 4-5 trillion barrels of oil [1].

Heavy oil is also called heavy oil. It not only has the characteristics of high viscosity and high specific gravity but also has low hydrogen to carbon ratio, high asphaltene content, high carbon residue, sulfur, nitrogen and heavy metal content, and high acid value [2, 3]. The difficulty in heavy oil production is high viscosity. Heating and upgrading are two effective ways to reduce viscosity.

With the continuous development of microwave technology, microwave heating technology has also been introduced into the production of heavy oil reservoirs. Its main purpose is to use the advantages of microwave heating, volume heating, and selective heating to heat the oil reservoir [4–6]. The efficiency of microwave heating depends on the dielectric loss constant of the heated material. Water, activated carbon, transition metals, and their oxides are strong microwave absorbing materials, while heavy oil absorbs microwaves very poorly [7]. Therefore, strong absorbing materials must be added to improve the absorbing ability of heavy oil. Some preliminary exploratory experiments have proved the technical advantages of microwave and nanoparticles in improving the recovery rate of unconventional oil reservoirs [8–13].

In recent years, scientists have proved through experiments that Fe_3O_4 particles can be used as a heavy oil adsorbent and catalyst compared with other nanoparticles, which can reduce the viscosity of heavy oil more effectively [14–21]. For example, a molecular sieve supported Fe_3O_4 catalyst was synthesized by microwave means. The synergistic effect of Fe_3O_4 and molecular sieve catalyzed the cracking of heavy oil. After 6 hours of reaction at 200°C, the viscosity reduction rate reached 92% [15]. Although the nanoparticle-assisted microwave performed well in the experiment of heating and viscosity reduction of heavy oil, it did not solve the problem of viscosity recovery. Nanoparticles will form localized high temperature after absorbing microwaves [22], which provides conditions for the addition of hydrogen donors to reform and viscosity reduction of heavy oil cracking. It can also further improve and reduce viscosity on the basis of heating and viscosity reduction, which greatly increases, and improve the viscosity reduction rate and effectively solve the problem of viscosity recovery.

This paper studies the mechanism of nanoparticle-assisted microwave heavy oil upgrading and enhanced oil recovery. First, the mechanism of nanoparticle-enhanced heat utilization efficiency of heavy oil is studied through the wave absorption and heating experiment of heavy oil. It is found that nanoparticles can improve the wave absorption and heating of heavy oil. It is found that the location of the nanoparticles during the microwave heating process will form a local high temperature, and the local high temperature provides a temperature condition for the cracking of heavy oil; then, a microwave-nanoparticle heavy oil upgrading and viscosity reduction study has been carried out, which proves that the method can be effectively upgraded and reduce the viscosity of heavy oil. Obtained the mechanism of nanoparticle-assisted microwave heavy oil to enhance oil recovery. The addition of catalyst improves the wave absorption and heating capacity of heavy oil, increases microwave energy utilization, and accelerates the heating rate of the oil reservoir in the microwave field, thereby using the viscosity-temperature characteristics of heavy oil to reduce the viscosity of heavy oil accelerates the exploitation of heavy oil; the nanoparticles form a high-temperature field under the action of microwave to catalyze the hydrocracking reaction between the heavy components in the heavy oil and the hydrogen donor to achieve the purpose of upgrading and reducing viscosity. These studies provide technical references for nanoparticle-assisted microwave heavy oil upgrading and enhanced oil recovery technologies and are of great significance to the development of technologies for further enhancing the recovery of heavy oil reservoirs.

2. Experiment

2.1. Materials and Instruments

2.1.1. Materials. Ultraheavy oil from Venezuela was used in these experiments, and Table 1 summarizes its properties. The Fe_3O_4 nanoparticles with particles sizes of 20 nm, 100 nm, and 10 μm were used (Aladdin Corporation). Tetrahydronaphthalene was used as the hydrogen donor (>98 wt% purity, Sinopharm Group). n-Heptane, petroleum ether, toluene, anhydrous ethanol, and neutral alumina were purchased from Sinopharm Group.

2.1.2. Instrument. The experimental device mainly includes microwave heater (Midea M1-L1213B, microwave power 231 385 539 700w, microwave frequency 2455 MHz, Qingdao Midea Co. Ltd. of China), Anton Paar rheometer, as shown in Figure 1, and oil drain system (oil drain funnel, glass beads, and oil receiving beaker), as shown in Figure 2.

2.2. Methods

2.2.1. Heating Test of Heavy Oil Using Nanoparticle-Assisted Microwaves. First, heavy oil was placed in a constant-temperature oven and heated to 80°C to make the heavy oil flowable, followed by its transfer into a 50 mL beaker. Second, ~45 g of heavy oil was weighed, and a certain concentration of the nanoparticles was added into the beaker. Third, the mixture was cooled to room temperature after stirring it well. Next, the beaker was placed in an M1-L1213B microwave heater (Midea, China; microwave frequency of 2450 MHz and maximum power of 700 W), the corresponding microwave power was set, and heating was started; and heavy oil was sampled out, and its temperature was measured every 2 min of heating. The temperature measurement was completed when the heavy oil was heated to ~110°C.

2.2.2. Local High-Temperature Experiment. First, place the heavy oil in a heating thermostat and heat it to 80°C to increase the temperature of the heavy oil and reduce its viscosity to flow, and transfer it to a 250 mL beaker; second, after the heavy oil drops to room temperature, place the beaker in a microwave heater for heating and measure the heating curve of the heavy oil without adding nanoparticles; take out the beaker, wait until the heavy oil is lowered to room temperature, add a small amount of nanoparticles to the beaker A, then place the beaker in a microwave heater for heating, and measure the temperature at two points A and B every 2 minutes until the temperature is reached; when reaching 90°C, the temperature rise curve at two points is obtained.

2.2.3. Upgrading of Heavy Oil Using Nanoparticle-Assisted Microwaves. First, the heavy oil sample was placed in a constant-temperature heating incubator and heated to 80°C to make the heavy oil warm to its flowable state. Second, the heated heavy oil was transferred to a 50 mL weighing

Table 1: Properties of ultraheavy oil from Venezuela.

Density at 50°C ($kg \cdot m^{-3}$)	Viscosity at 25°C (mPa·s)	Viscosity at 50°C (mPa·s)	Saturates (wt%)	Aromatics (wt%)	Resin (wt%)	Asphaltenes (wt%)
976.5	1380000	100400	25.70	35.25	27.05	12.00

Figure 1: Antongpa rheometer.

Figure 2: Heavy oil gravity drainage device.

bottle for weighing ~45 g of heavy oil. Third, the catalyst and hydrogen donor were added to reach certain mass contents, and the mixture was stirred until a homogeneous system was formed, and then cooled to room temperature. The weighing bottle was placed into a microwave heater; the microwave power and heating time were set; the oil sample was removed after heating; and relevant measurements were performed after cooling, including the viscosity measurement of crude oil viscosity and four-component test.

Viscosity measurement of crude oil: a planar laminar system of an MCR rheometer (Anton Paar, Austria) was used, and the test parameters were set to a speed of 170 s^{-1} and a temperature range of 20–100°C.

Four-component determination: first, asphaltenes were removed from the oil sample, followed by the dilution and dissolution of the sample with 10 mL of petroleum ether. Second, an adsorption column was connected to an ultraconstant temperature water bath, and the temperature of the circulating water was maintained at 50°C. Third, the lower end of the adsorption column was plugged with a small amount of degreased cotton, the column was filled with alumina till 7 cm below the circulating water level of the column, and then 30 mL of petroleum ether was added to prewet the adsorption column after tapping. As all the petroleum ether for prewetting entered the alumina layer, the diluted sample was added, and petroleum ether was used to wash the conical flask thrice. The washing solution was poured into the adsorption column. After all the sample solution entered into the alumina layer, the solution was covered with 3 cm thick alumina. Each component was rinsed, and its mass was recorded at the end of the experiment for calculating the proportion of four components in the sample [15, 16].

2.2.4. Gravity Drainage Test of Heavy Oil under Microwave Heating. The oven temperature was set to 80°C, and the beaker with heavy oil was placed in an oven for heating. The connection of the gravity drain device is shown in Figure 3. After the heavy oil reached a flowable state, the heavy oil was removed into a 250 mL beaker, and the sample was measured with a mass of m_1. According to m_1, the chemicals with the corresponding mass percentages were added and stirred with a glass rod; the weight of this sample was designated as m_2. The glass bead with a mass of m_3 was weighed, the glass beads were mixed with the heavy oil, transferred into a drainage funnel, and the mass of residual heavy oil in the beaker was measured to be m_4. The mass difference between m_2 and m_4 corresponded to the total amount of heavy oil in the drainage funnel and the mass of the oil-receiving beaker, which was measured as m_5. As the heavy oil in the drainage funnel cooled to room temperature, the drainage system was placed into a microwave heater, the microwave power was set, and the experiment was started. During the experiment, the drainage system was taken out every 2 min, and the mass of the oil-receiving beaker was measured to be m_6 using an analytical balance. m_6-m_5 referred to the mass of output oil. An infrared thermometer was used to measure the temperature of the heavy oil (T1) until the recovery amount of the heavy oil did not increase, and the experiment was completed. According to the measurement data, the production curve was drawn, and the effect of each influencing factor on the microwave drainage experiment of heavy oil was compared and analyzed. Figure 1 shows the schematic of the microwave gravity drainage experiment of heavy oil.

3. Results and Discussion

3.1. Research on the Mechanism of Nanoparticles to Enhance the Heat Utilization Efficiency of Heavy Oil

3.1.1. Research on Nanoparticles to Improve the Absorbing and Heating Ability of Heavy Oil. The experimental

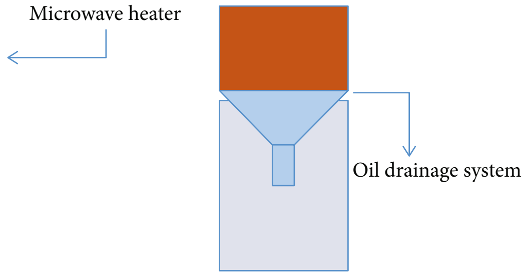

Figure 3: Schematic of the gravity drainage test of heavy oil under microwave heating.

nanoparticle is 100 nm Fe3O4, the microwave power is 539 W, and the curve of the temperature of the heavy oil with time when the nanoparticle of different mass concentration is added is obtained, as shown in Figure 4.

It can be found from Figure 4 that under the condition of an initial temperature of 24°C, the oil sample with nano-Fe_3O_4 nanoparticles added has a higher temperature than the crude oil sample heated by microwave for the same time. As the mass concentration of nano Fe_3O_4 nanoparticles increases, the time it takes to reach the same temperature is shorter. This is because nano-Fe_3O_4 nanoparticles have a large dielectric constant and have a stronger absorbing effect on microwaves, indicating that the addition of nano-Fe_3O_4 nanoparticles improves the wave-absorbing and heating ability of heavy oil.

3.1.2. Microwave-Nanoparticle Local High-Temperature Experimental Research. The nanoparticle used in the experiment is 100 nm Fe_3O_4, and the microwave power is set to 539 W. In the experiment, the heating curve of the microwave heating heavy oil as it is and the heating curve of the two points A and B after adding nanoparticles are shown in Figure 5.

Observing Figure 5, it can be found that the heating rate of point A is faster than that of point B, and the heating rate of heavy oil is the slowest. This is because the nanoparticles of point A quickly convert microwave energy into heat energy. Point A is the first to heat up to form a local high temperature and drive the thick oil. The overall temperature of the oil accelerates, so the heating rate of point B is faster than that of the original control group of heavy oil. This shows that during the microwave heating process, the location of the nanoparticles will form a local relatively high temperature, which provides a temperature condition for the cracking of heavy oil.

3.2. Nanoparticle-Assisted Microwave Heavy Oil Upgrading and Viscosity Reduction

3.2.1. Microwave-Nanoparticle Heavy Oil Upgrading Verification Experiment. The nanoparticles used in the experiment were 100 nm magnetic iron oxide nanoparticles, and the hydrogen donor was tetralin. The viscosity-temperature curves of the four groups of heavy oil samples after microwave treatment are shown in Figure 6.

Comparing the original heavy oil and the heavy oil with only nanoparticles, it can be found that the viscosity of the heavy oil in the control group with only nanoparticles is increased. Due to the high-temperature environment, the long chain of the heavy components is broken, but because there is no hydrogen supplementation, it cannot happen. Hydrogenation reaction, so the broken long chain will recombine. And because the experimental environment is not sealed, the light components in the heavy oil evaporate and lose at high temperatures, so the viscosity becomes higher; comparing the original heavy oil and the heavy oil with only hydrogen donors, it can be found that the viscosity of the control group with only hydrogen donors has decreased. The analysis believes that the viscosity reduction effect of tetralin is due to the dilution and viscosity reduction effect of tetralin, and it may also be modified by heating to the cracking temperature. Four-component analysis is required for further verification; observing the viscosity reduction system of the experimental group, the experimental group can find that the viscosity reduction effect of the experimental group with heavy oil added to the viscosity reduction system is the best. Analysis suggests that the viscosity reduction of heavy oil occurred during the process, and the reduction of asphaltene content resulted in a significant decrease in viscosity.

In order to further verify the experimental results, a four-component analysis test was carried out to calculate the proportion of the four components. The results are shown in Figure 7.

Comparing experiments 1# and 2#, the aromatic content increased, and the rest decreased, but the overall change was small, mainly because the added hydrogen donor was an aromatic hydrocarbon, and the decrease in viscosity of the control group was mainly due to the effect of dilution. Comparing experiment 1# and 3#, the light components are reduced, mainly because the addition of nanoparticles provides a high-temperature environment, and the hydrogenation reduction reaction cannot occur under the condition of high temperature without hydrogen donor, and because of the high temperature, the light components are volatilized loss. Comparing experiment 1# and 4#, the asphaltenes are obviously reduced, and the gums are increased. This is because the asphaltenes will be partially converted to gums during the upgrading process, and the content of asphaltenes is the main influence on the viscosity of heavy oil. This also explains the reason for the significant drop in viscosity in the viscosity-temperature curve.

3.2.2. Research on Viscosity Recovery of Microwave-Nanoparticle Heavy Oil Upgrading. The hydrogen donor used in the experiment was tetralin, the nanoparticles were 100 nm Fe_3O_4 particles, the microwave heating power was set to 539 W, and the microwave heating reaction time was 60 min.

The viscosity-temperature curve of the thick oil obtained in the third group of upgrading experiments was measured, the viscosity-temperature curve of the retained heavy oil samples was measured again at 3 days, 7 days, and 14 days

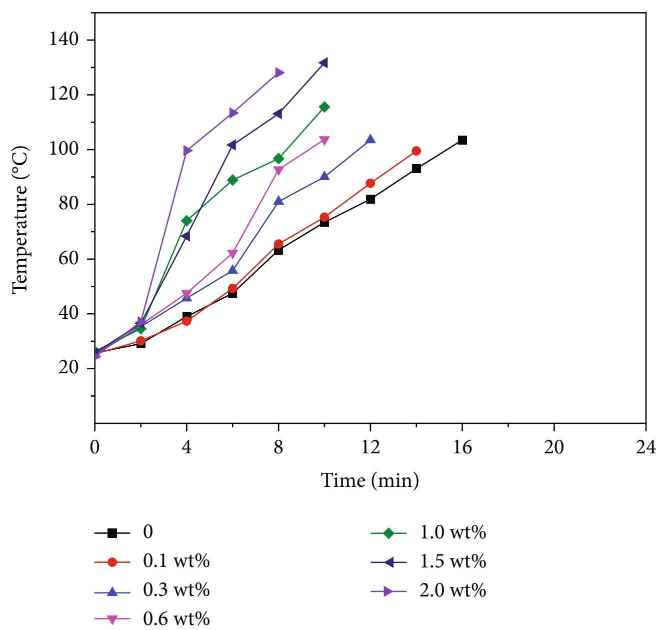

Figure 4: Temperature curves of heavy oil with time under different mass fractions of nanoparticles.

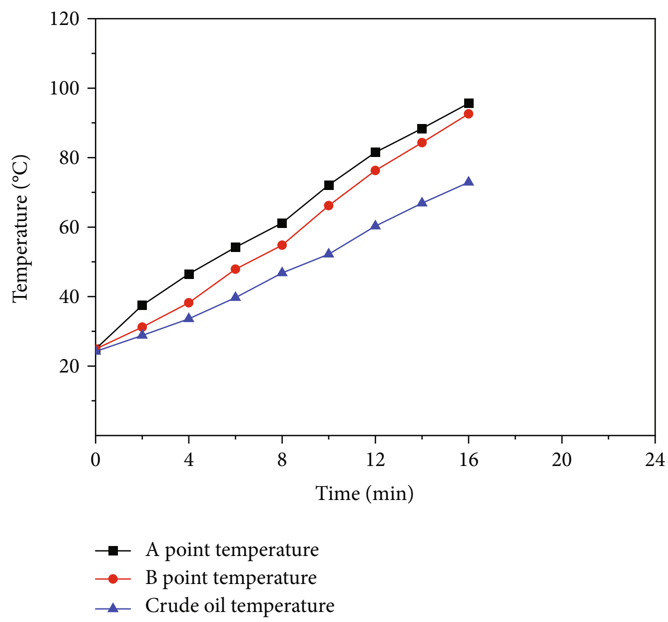

Figure 5: Temperature curve of heavy oil heated by microwave with time.

after the end of the experiment, and the viscosity of the modified heavy oil was observed. The recovery situation, the experimental results are shown in Figure 8.

At present, the commonly used index to evaluate the viscosity reduction ability is the viscosity reduction rate, that is, the percentage of the viscosity reduction of the super heavy oil after adding the viscosity reducer. In order to express its viscosity reduction effect more intuitively, compare the viscosity and viscosity reduction rate of heavy oil at 50°C. The results are shown in Figure 9.

Observing Figures 8 and 9, it can be found that within seven days after the microwave-nanoparticle heavy oil upgrading experiment, the viscosity has a relatively obvious recovery, but on the 14th day, it is found that the viscosity of the heavy oil remains stable, and the viscosity is still much lower after recovery. The viscosity of heavy oil is diluted by adding 5 wt% hydrogen donor as it is. Experiments have proved that there is viscosity recovery in microwave-nanoparticle heavy oil upgrading and viscosity reduction, but its viscosity reduction effect is still significant.

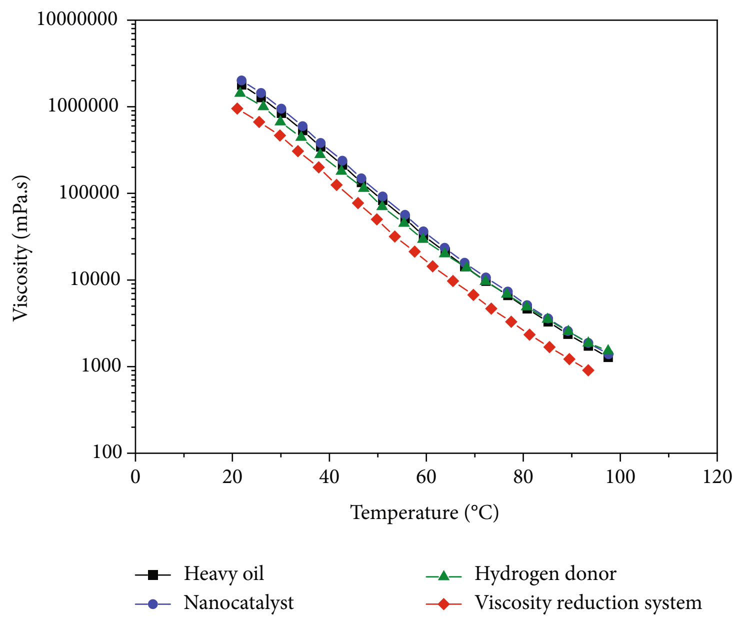

Figure 6: Viscosity-temperature curves of heavy oil obtained from each group of experiments.

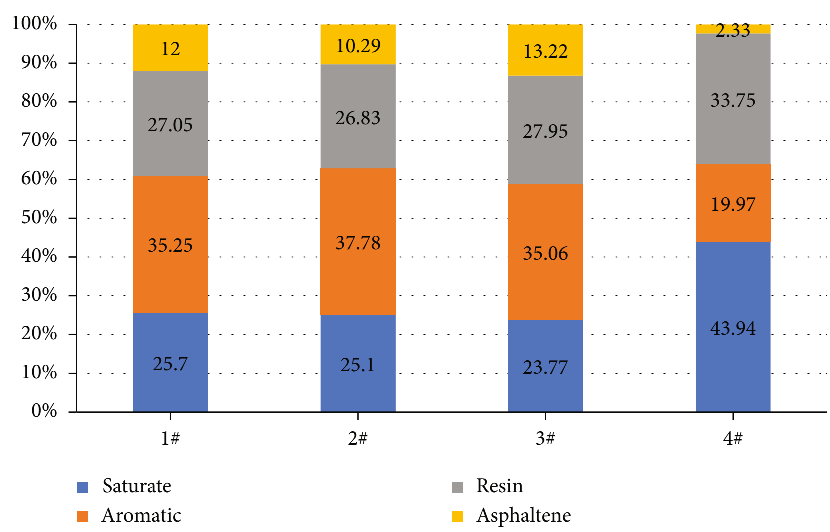

Figure 7: The proportion of four components.

3.3. Nanoparticle-Assisted Microwave Heavy Oil Enhanced Oil Recovery Research

3.3.1. The Influence of Water Content on the Microwave Heavy Oil Drainage Experiment. According to the temperature data measured in the experiment, the regression data obtains the linear slope of one yuan, that is, the heating rate of the heavy oil in the porous medium during the oil drainage process, as shown in Table 2. It is observed that when the water content is increased to 5%, there is a significant increase in the heating rate, while the increase in the water content from 5% to 10% reduces the heating rate of the heavy oil. The addition of water can effectively improve the wave absorption and heating capacity of the reservoir, but the increase in water cut has little effect on the increase in heating rate.

Calculate the recovery factor of the heavy oil in each group of experiments, and get the curve of the recovery factor of heavy oil drainage experiment with time under different water cuts, as shown in Figure 10. It is observed that the two groups of experimental curves with a moisture content of 5% and 10% are similar, and the production time is significantly shortened compared with the control group without moisture.

Calculate the oil production rate of each group of experimental heavy oil and obtain the curve of the oil production rate of the heavy oil drainage experiment with time under different water cuts, as shown in Figure 11. It is observed

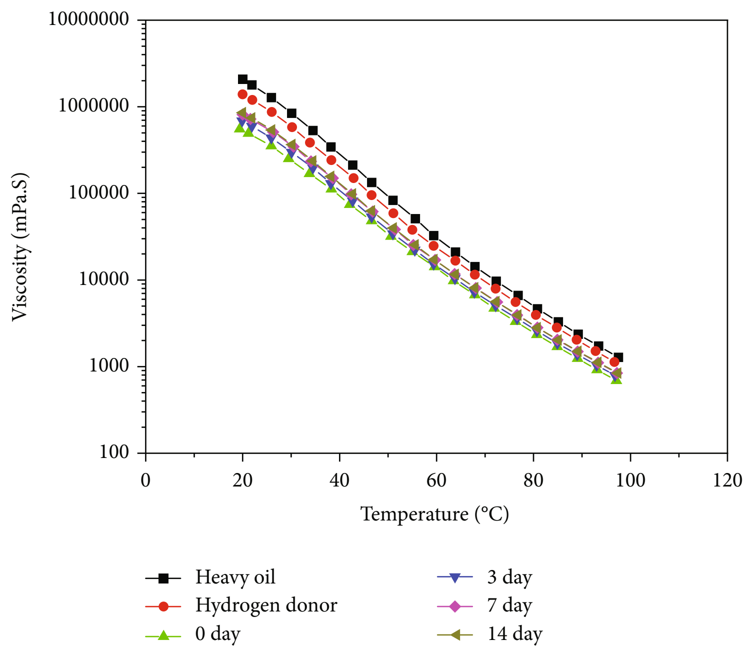

Figure 8: Viscosity-temperature curves of heavy oil obtained from each group of experiments.

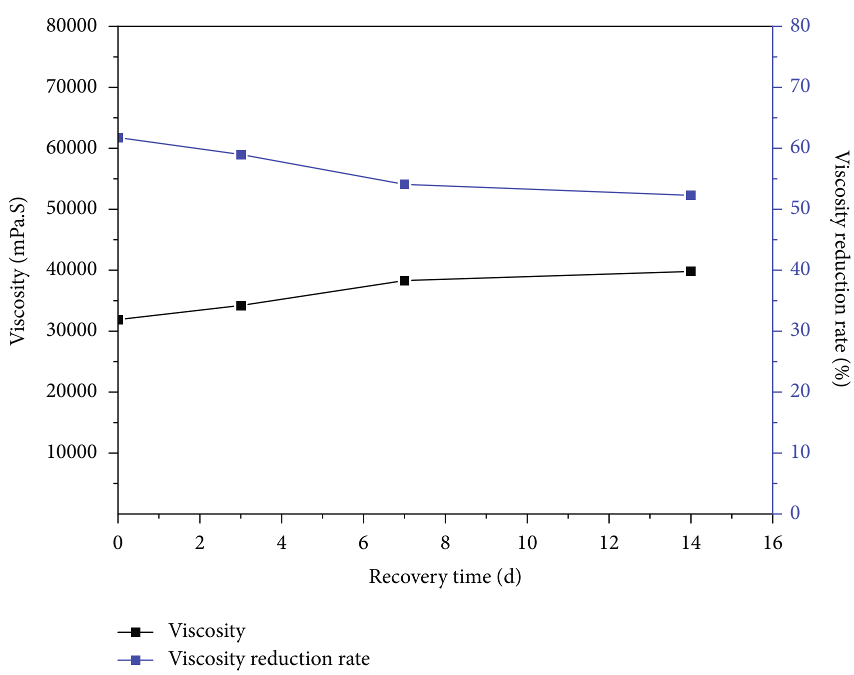

Figure 9: Viscosity and viscosity reduction rate curve changes with recovery time after reaction.

Table 2: Experimental heating rate under different moisture content.

Serial number	Water cut (%)	Heating rate (°C/min)
1#	—	3.132
2#	5	5.2545
3#	10	5.1164

that the two sets of experiments with water can reach the high-speed production period earlier. The analysis suggests that the wave absorption and heating ability of the heavy oil are improved after the addition of water, which accelerates the temperature rise of the heavy oil, and then the viscosity decreases rapidly, so the fluidity of the heavy oil enhances so the oil production rate can reach the peak earlier.

Take the data of 8 minutes and 16 minutes of each experiment for comparative analysis. At 8 minutes and 16

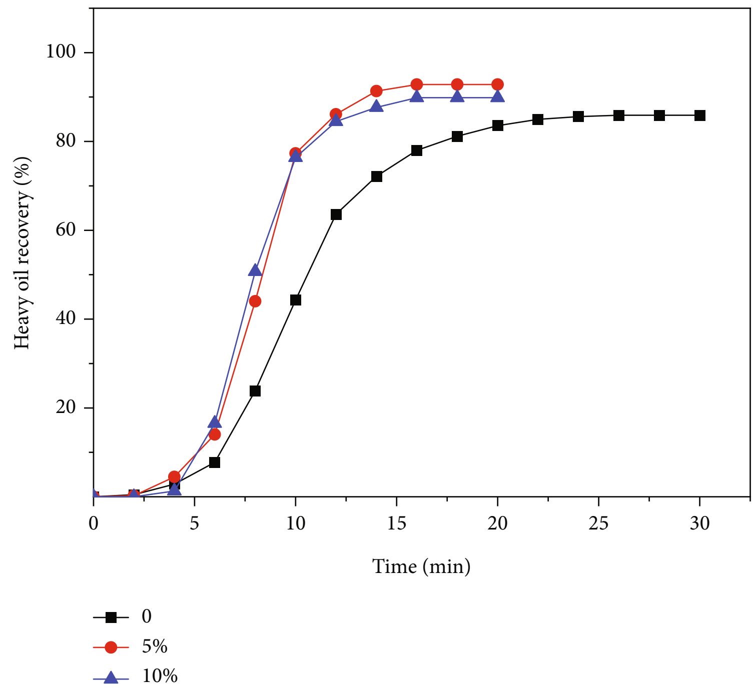

Figure 10: The experimental heavy oil recovery curves of each group under different water content.

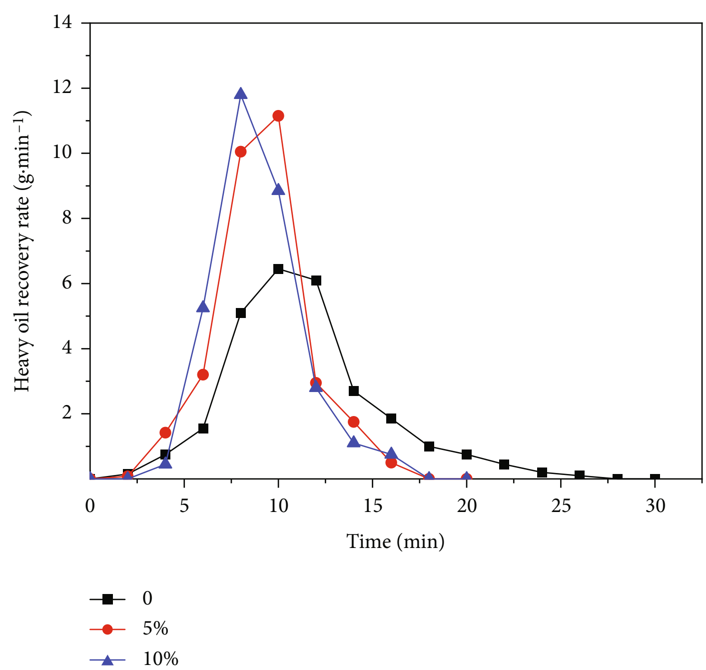

Figure 11: The experimental heavy oil recovery rate curves of each group.

minutes, 2# and 3# are the water-bearing experimental groups, and the temperature is about 10°C higher than that of the 1# heavy oil original sample group, which proves the addition of water accelerates the heating rate of the heavy oil drainage system and improves the wave absorption and heating ability of the heavy oil system; comparing the recovery factor and oil production rate at 8 minutes, it can be found that the 2# and 3# water-bearing experimental groups are thick. The oil is about twice as much as the control group, because the addition of water increases the heating speed of the heavy oil system, the viscosity of the heavy oil increases, the fluidity increases, the gravity driving effect is enhanced, and the faster oil production rate can be achieved. Corresponding to an increase in oil recovery; comparing the oil production rate and recovery efficiency of each group of experiments at 16 minutes, it can be found that the oil production of the experimental groups with water cuts of 5% and 10% has slowed down and the oil recovery has reached the maximum, while the original heavy oil control group is still in production; comparing the production time, the time used in the experimental group with 5% and 10% water content is 10 minutes shorter than that of the original heavy oil, which proves that the presence of water accelerates production; the final recovery rate is in terms of water content in the latter two groups of experiments, although there is boiling and evaporation during the experiment, the final recovery rate is higher than that of the original heavy oil control. The analysis believes that the addition of water increased the final recovery rate of heavy oil.

In summary, it is believed that the presence of water in the heavy oil system can effectively improve the wave absorption and heating capacity of the heavy oil, speed up the temperature rise of the reservoir, make the heavy oil heated quickly reduce the viscosity, enhance the fluidity of the heavy oil, and accelerate the gravity drainage of the heavy oil.

3.3.2. The Influence of Nanoparticle Size on Microwave Heavy Oil Drainage Experiment. According to the temperature data measured in the experiment, the regression data obtains the linear slope of one yuan, that is, the heating rate of the heavy oil in the porous medium is physically simulated during the oil drainage process. The heating rate of the heavy oil with different size nanoparticles is shown in Table 3. It is observed that the addition of 20 nm and 100 nm magnetic iron oxide nanoparticles has similar lifting effects on the heavy oil system, while the 10 μm nanoparticles have little effect on the improvement of the heating rate of the heavy oil system.

Calculate the recovery factor of each group of experimental heavy oil and obtain the curve of heavy oil recovery overtime in the heavy oil drainage experiment under different particle size nanoparticles, as shown in Figure 12. It was observed that the two experimental curves with nanoparticles were similar, and the curves of the experimental group with micron nanoparticles were between the nanometer and the original. The production of the two types of nanoparticles was the fastest, and the final recovery efficiency of the four groups of experiments was similar.

The oil production rate of each group of experimental heavy oil was calculated, and the oil production rate of the heavy oil drain experiment with different particle diameters of nanoparticles was obtained with time, as shown in Figure 13. It was observed that the oil production rate of the two groups of experiments with nanometer-sized nanoparticles reached the maximum earlier, nanometer-level.

At 8 minutes and 16 minutes, the temperature of the experimental group with nanosized nanoparticles was the highest, followed by microsized magnetic iron oxide nanoparticles. Nano- and microsized magnetic iron oxide nanoparticles improved the absorption of the heavy oil drainage system during the heavy oil drainage experiment. The improvement effect of the wave heating ability, nanometer level is better than micron level.

Table 3: Heating rate of each group.

Serial number	Catalyst particle size	Heating rate (°C/min)
1#	—	3.0916
2#	20 nm	5.3358
3#	100 nm	5.4348
4#	10 μm	4.3886

Comparing the recovery rate and oil production rate at 8 minutes, it can be found that the experimental group with nanometer-sized nanoparticles has a faster oil production rate and a higher recovery rate, followed by the micron level. The analysis believes that because the nanoscale nanoparticles assisted heavy oil to heat up faster in the microwave, the viscosity of the heavy oil decreases faster, the fluidity of the heavy oil increases, and the oil drainage production is accelerated by the action of gravity displacement.

Comparing the oil recovery and oil production rate of each group of experiments at 16 minutes, the two groups added nanosized nanoparticles in the experimental group have the slowest oil production rate, and the recovery factor is close to the final recovery factor, and then observe the production time to further confirm. The addition of nanosized nanoparticles effectively shortens the production time. Micron-sized nanoparticles have the same effect, but the effect is inferior to that of nanosized nanoparticles. In terms of ultimate oil recovery, the final oil recovery of the four groups of experiments is similar, and the addition of nanoparticles has no effect on the ultimate oil recovery.

In summary, the addition of magnetic iron oxide nanoparticles to the heavy oil system during the microwave gravity drainage experiment can effectively speed up the temperature of the system, accelerate the rate of oil production, and shorten the production time, and the effect of nanosized nanoparticles is better than microsized nanoparticles.

3.3.3. The Influence of Nanoparticle Mass Concentration on Microwave Heavy Oil Drainage Experiment. According to the temperature data measured in the experiment, the regression data obtains the linear slope of one yuan, that is, the heating rate of the heavy oil in the porous medium during the physical simulation of the oil drainage process, as shown in Table 4. It can be found that as the mass concentration of nanoparticles increases, the heating rate increases significantly.

The recovery factor of each group of experimental heavy oil was calculated, and the recovery factor of heavy oil drainage experiment with different nanoparticle mass concentrations was obtained with time, as shown in Figure 14. It can be found that as the mass concentration of nanoparticles increases, the oil drainage experiment can reach the maximum recovery factor earlier, the production time is shortened, and the final recovery factor is similar.

Calculate the oil production rate of each group of experimental heavy oil and obtain the curve of the oil production rate of the heavy oil drainage experiment with time under different nanoparticle mass concentrations. As shown in

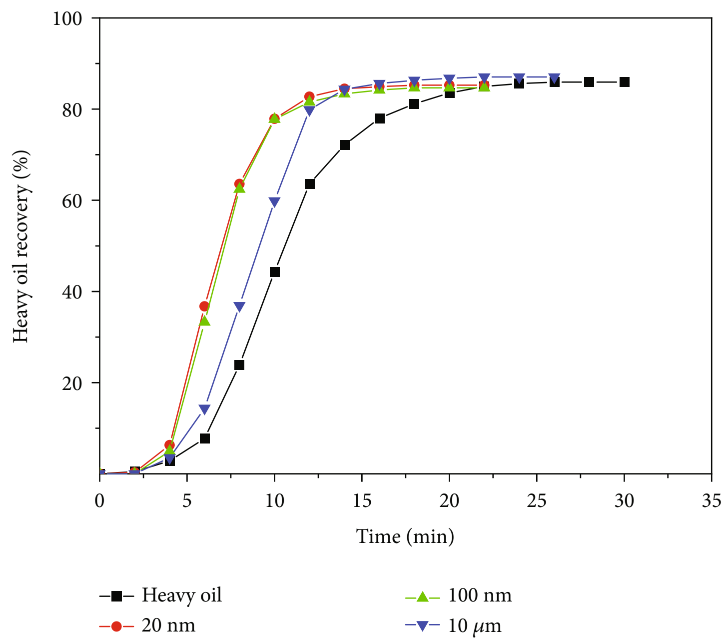

Figure 12: The experimental heavy oil recovery curves of each group under different water content.

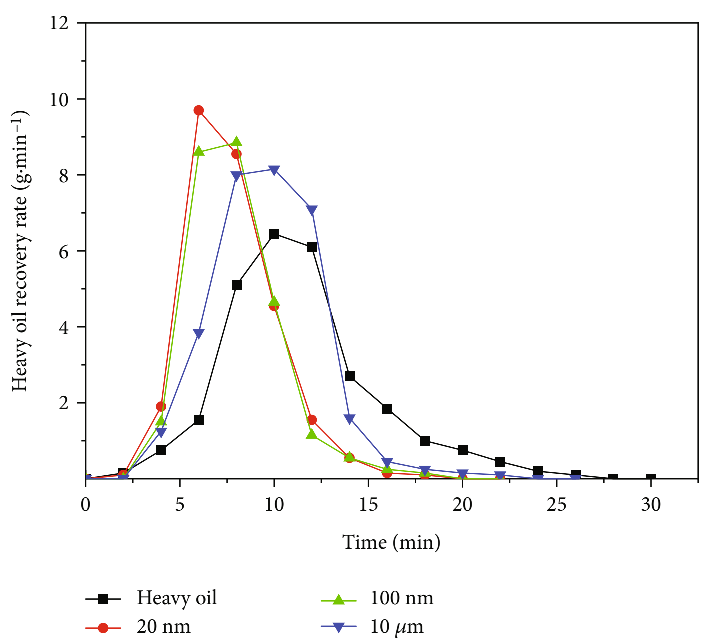

Figure 13: The experimental heavy oil recovery rate curves of each group under different water content.

Table 4: Experimental heating rate under different catalyst mass concentration.

Serial number	Mass (%)	Heating rate (°C/min)
1#	—	3.09
2#	0.1	5.34
3#	0.5	5.43

Figure 15, it can be found that the higher the nanoparticle mass concentration added, the higher the production rate.

At 8 minutes and 16 minutes, the higher the mass concentration of nanoparticles added, the faster the temperature of the measured heavy oil drainage system will rise. The higher the mass concentration of nanoparticles, the better the effect of improving the wave absorption and heating capacity of the heavy oil drainage system during the heavy oil drainage experiment.

Comparing the recovery rate and oil production rate at 8 minutes, it can be found that the higher the mass

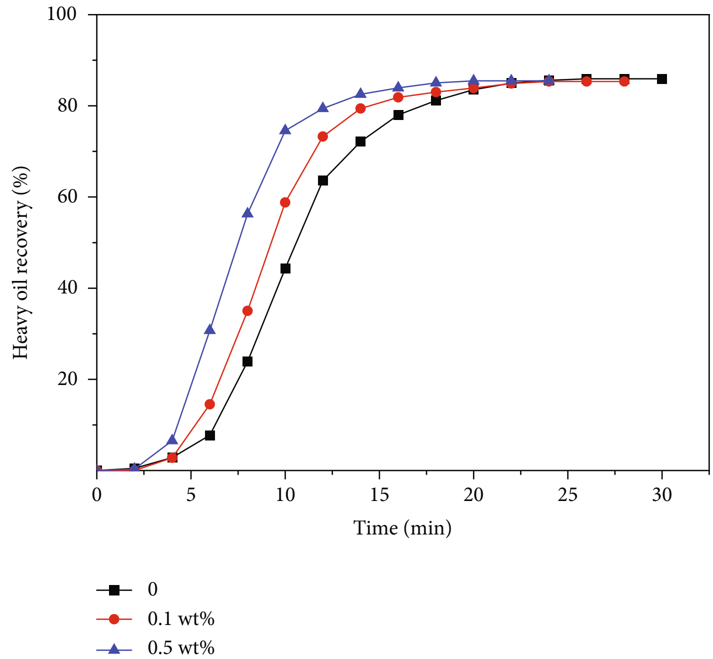

Figure 14: The experimental heavy oil recovery curves of each group under different mass fractions of nanoparticles.

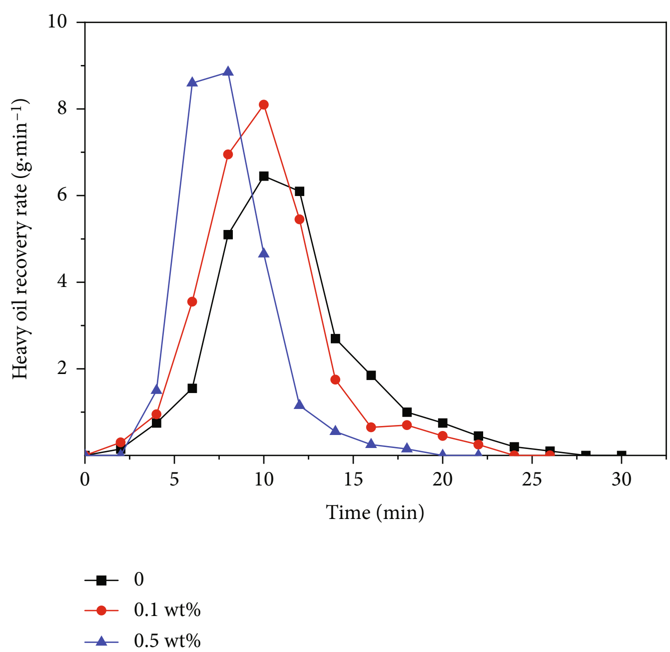

Figure 15: The experimental heavy oil recovery rate curves of each group under different mass fractions of nanocatalysts.

Table 5: Different microwave power experiment heating rate.

Serial number	Microwave power (W)	Heating rate (°C/min)
1#	385	3.0916
2#	539	4.2282
3#	700	5.2621

concentration of rice nanoparticles in the experimental group, the higher the oil production rate and oil recovery rate. This is because when the temperature rises faster, the viscosity of the heavy oil decreases faster, the fluidity is rapidly enhanced, the gravity drive is more obvious, and the rate of oil production is accelerated.

Comparing the recovery factor and oil production rate of each group of experiments at 16 minutes, it can be found that the higher the mass concentration of rice nanoparticles, the slower the oil production rate, and the closer the

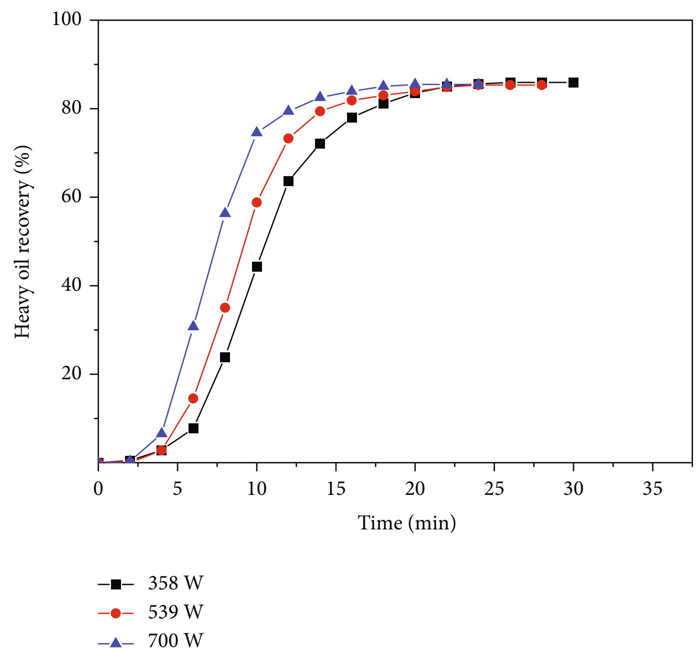

Figure 16: The experimental heavy oil recovery curves of each group under different microwave power.

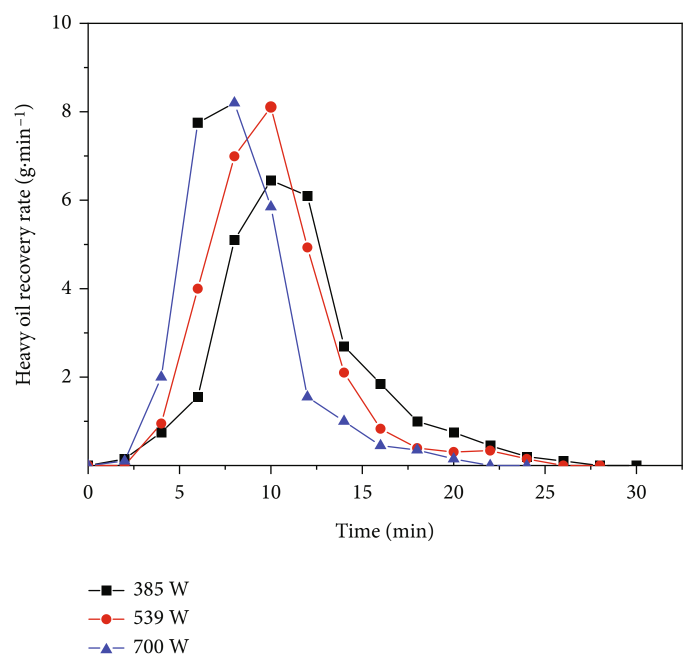

Figure 17: The experimental heavy oil recovery rate curves of each group under different microwave power.

recovery factor is to the final recovery factor. By observing the production time, it can be further determined that the higher the mass concentration of nanoparticles, the shorter the production time; in terms of the final recovery factor, the three sets of experiments have similar final recovery factors, and the addition of nanoparticles has no effect on the final recovery factor.

In summary, adding nanoparticles to the heavy oil system can effectively speed up the temperature of the heavy oil system, accelerate the oil production rate, and shorten the production time during the microwave gravity drainage experiment. The higher the amount added, the more obvious the improvement effect.

3.3.4. The Influence of Microwave Power on Microwave Heavy Oil Drainage Experiment. According to the temperature data measured in the experiment, the regression data obtains a linear slope of one yuan, that is, physical simulation of the heating rate of heavy oil in porous media during oil drainage. As shown in Table 5, it is found that as the microwave power increases, and the heating rate increases.

The recovery factor of each group of experimental heavy oil is calculated, and the recovery factor of the heavy oil drain experiment with different microwave power numbers is obtained with time, as shown in Figure 16. It can be found that with the increase of microwave power, the heavy oil drainage experiment can reach the maximum recovery factor earlier, the production time is shortened, and the final recovery factor is similar.

Calculate the oil production rate of each group of experimental heavy oil and obtain the oil production rate of heavy oil drainage experiment with time under different nanoparticle mass concentrations, as shown in Figure 17. It can be found that as the microwave power increases, the production speed can reach the fastest value earlier.

Comparing the temperature data at 8 minutes and 16 minutes, it is found that the higher the microwave power, the faster the heating of the heavy oil system will be. The higher the microwave power, the more energy is provided for the heavy oil system, and the heating of the heavy oil system is accelerated.

Comparing the recovery factor and oil production rate at 8 minutes, it can be found that the higher the microwave power of the experimental group, the faster the oil production rate and the higher the recovery factor. This is because when the temperature rises faster, the viscosity of the heavy oil decreases faster, the fluidity increases rapidly, and the rate of oil discharge and oil production speeds up due to the action of gravity driving.

Comparing the recovery factor and oil production rate of each group of experiments at 16 minutes, it can be found that the higher the microwave power, the slower the oil production rate, and the closer the recovery factor is to the final recovery factor. Observing the production time, it can be further determined that the higher the microwave power, the shorter the production time; in terms of the final recovery factor, the final recovery factors of the three experiments are similar, and the microwave power has no effect on the final recovery factor.

To sum up, the higher the microwave power, the more energy can be provided to the oil reservoir, which can accelerate the temperature of the oil reservoir, thereby accelerating production and shortening the production time.

4. Conclusion

(1) The mechanism of nanoparticles to enhance the heat utilization efficiency of heavy oil is obtained. Nanoparticles can effectively improve the wave absorption and heating capacity of heavy oil, and the improvement effect will be enhanced with the increase of the amount of addition. In addition, during the microwave heating process, the location of the nanoparticles will form a high-temperature field. This local high temperature provides temperature conditions for the cracking of heavy oil

(2) It is proved that the method of nanoparticle-assisted microwave heating of heavy oil can effectively upgrade oil and reduce the viscosity of heavy oil, reducing the asphaltene content and viscosity of the heavy oil

(3) The method of nanoparticle-assisted microwave upgrading and viscosity reduction of thick oil has the problem of viscosity recovery, the final viscosity reduction rate is stabilized at 50%, and the viscosity reduction effect is still very obvious

(4) Completed the research on the factors affecting the gravity drainage of microwave heavy oil. Water and nanoparticles can improve the wave absorption and heating capacity of heavy oil, accelerate the heating of heavy oil, and reduce the viscosity of heavy oil rapidly, thereby shortening the production time of heavy oil drainage and accelerating the production of heavy oil

Abbreviations

IEA: International Energy Agency.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no competing financial interest.

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