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ORIGINAL RESEARCH PAPER

The Potential of ZnO Nanoparticles to Reduce Water Consuming in Iranian Heavy Oil Reservoir

Masoumeh Tajmiri*, Mohammad Reza Ehsani

Department of Chemical Engineering, Faculty of Chemical Engineering, Isfahan University of Technology, Isfahan, Iran

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ABSTRACT
Water is critically important, because its supply is under stress. In oil fields, the ratio-of-water-to-oil (WCUT%) can be 95% or higher. Managing this produced water is a great challenge whereas the best opportunity to reduce costs, improve profitability and preserve the natural environment. The oil industry is looking for more effective ways to reduce water consuming and improve the recovery rates. Nano materials are an obvious place to look. This study provides new insights into ZnO nanoparticles effects on residual oil saturation (SOR) and WCUT% through steam assisted gravity drainage (SAGD) process by experimental work. Laboratory tests were conducted in two experiments through the use of 2 dimensional scaled SAGD cell from an Iranian heavy oil reservoir. In the first experiment, the SAGD cell was saturated with heavy oil and in the second one, the cell was flooded with nanoparticles before saturation with oil. The amount of recoveries were monitored during 12 hours. Results show that the ultimate oil recoveries increase from 52.43% to 87.93% by adding ZnO nanoparticles, respectively. The experimental results provide the nanoparticles ability to reduce produced water and minimize fresh water use can contribute to water conservation.

KEYWORDS: *Nanoparticles; Steam Assisted Gravity Drainage; ZnO*

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INTRODUCTION

The oil and gas industry is undergoing a series of dramatic shifts with one common outcome, extracting hydrocarbons is harder than ever before. Production from the world's largest conventional fields is in decline while national oil companies continue to control the majority of the world's oil reserves. Simultaneously, global demand for oil and gas continues to grow, fueled in large part by emerging economies.

As a result, producers have resorted to new techniques to bypass declining and inaccessible legacy sources of oil and gas. The last five years have seen a dramatic increase in production from unconventional sources. These source, shale, oil sands and deep water offshore, represented 47 percent of capital spending in oil industry in 2016. Producers are using more to get less, more labor, more energy, more time and more water which all lead to higher costs for both producers and consumers. From the water used to flood declining conventional and offshore wells to the water injected to fracture underground shale to the steam required for oil sands extraction. Water is the most important input to the oil and gas industry. By 2030, if current trends continue,

* Corresponding Author Email: maral.tajmiri@gmail.com

Table 1. Experimental conditions and purposes of two steps

Step No of runs	Process	Purpose	Model width × height (cm^2)	length (cm)	Pressure difference (KPas)
Step I	Usual SAGD	Effect of well spacing	20 × 20	15	20
Step II	Usual SAGD	Effect of ZnO nanoparticles	20 × 20	15	20

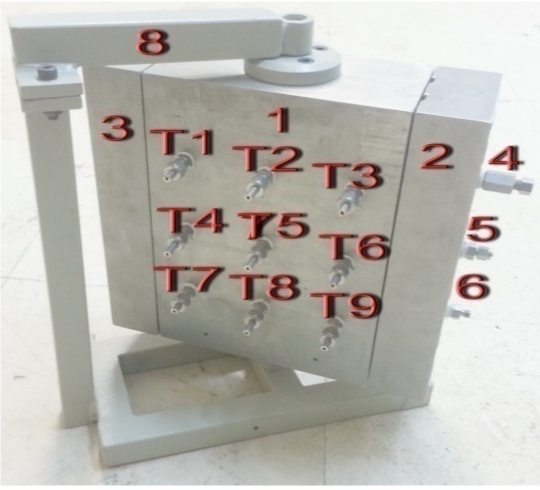

Fig. 1. The schematic of physical model;
1- The main body with inside dimensions 20×20×4 cm; 2- Upper cap with dimensions of 31.5×25.8×11 cm; 3- Lower cap with dimensions of 31.5×25.8×11 cm; 4- Steam injector well in 15 cm from producer; 5- Steam injector well in 10 cm from producerp; 6- Oil producer well in the bottom of model; 7- A total of 9 thermocouple (T1-T9) probes installed to the model. The thermocouples connected to the data acquisition instrument, which recorded and displayed the temperature profile within the model during the experiment; 8- The basis for rotating the model in different angels.

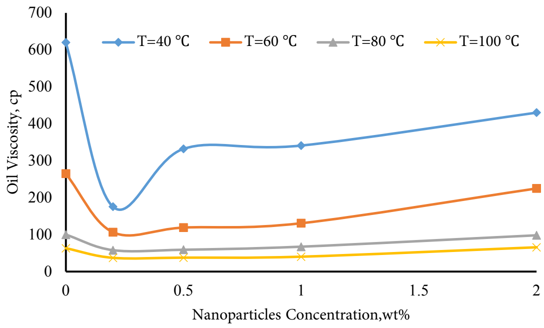

Fig. 2. The effect of different concentrations of ZnO nanoparticles on heavy oil viscosity.

global water requirements are expected to exceed supplies by forty percent. This trend is all the more relevant in oil and gas production, as many of the world's largest reserves reside in the most water-starved regions. Oil and gas producers should be concerned with water not only as a proactive step to be more efficient, but also as a defensive step against declining water supplies. From chemical and mechanical conformance tools to custom water treatment, water challenges with processes and technologies that reduce unwanted water production and treat produced water for disposal or reuse while satisfying a broad range of reservoir management and environmental objectives are solved. Globally, oil wells produce about 220 million BWPD (barrels of water per day) roughly three barrels of water for every barrel of oil. In older fields, the WCUT% can be 95% or higher. Managing this produced water is a great challenge for operators. Rising prices for energy coupled with the increasing environmental awareness of consumers are responsible for a flood of products on the market that promise certain advantages for environmental and climate protection. Nanotechnology exhibits special physical and chemical properties that makes it interesting for novel and environmentally friendly products. In the chemical industry sector, nano materials are applied based on their special catalytic properties in order to boost energy and resource efficiency and nano materials can replace environmentally problematic chemicals in certain fields of application. High hopes are being placed in nanotechnology optimized products and processes for energy production and storage. These are currently in the development phase and are slated to contribute significantly to climate protection and solving our energy problems in the future [1]. The capability of nanotechnology usage in enhanced oil recovery processes is investigated. The rock pores may contain trapped oil, gas and water. Nanoparticles can be used to recover more residual oil. It is showed that nanotechnology affects on several parameters such as oil viscosity reduction [2]. High surface-to-volume ratio of nano fluids leads to improve thermal properties. The surface-to-volume ratio of nanoparticles may be 1000 times greater than of micro particles. It is tested a variety of particle sizes and types to find those best suited for plugging the rock pores, which turn out to be elastic nanoparticles made of polymer

Table 2. Properties of the oil used

Name	Oil density (API)	Dead oil viscosity (at 7.158 °C) (cp)	Compressibility (psi ^{1})	Thermal expansion factor (from 4 to 12.421°C) (°C ^{1})
KM	13	16000	4.67×10 ^{6}	4.00 × 10 ^{4}

Table 3. Specifications of ZnO nanoparticles used

Particle type	Formula	Form	Purity	Absolute particle size	Specific surface area	Appearance
Zinc oxide	ZnO	Nano powder	99%	<50 nm	>60 m^2g^{-1}	White powder

threads that retract into coils. Nanoparticles in solid form such as silica are less effective [3]. The effect of nano sized metal on decreasing viscosity through thermal process is reported. The results provide a good understanding of viscosity mechanism [4]. Silica nanoparticles fluid is flooded in water-wet sandstone and investigated the hydrophilic or hydrophobic monolayer role of them in the pore spaces. It is found that adsorption of SNPs can help to alter reservoir wettability [5]. Wettability can be changed depending on nanoparticles type through altering the chemical interactions in interfacial tension [6]. The oil recovery is increased about 4-5% compared to brine in the core flooding procedure by nano fluids. Hence, the potential of nanoparticles enhanced oil recovery is clear. The experimental results show that the IFT between water phase and oil phase can be reduced by nano fluids and the wettability of solid surface alters to more water wet and releasing oil drops by increasing capillary pressure is completely obvious [7]. Nano-size metal particles is used to reduce viscosity of heavy oil/bitumen through steam injection techniques. The experiments are a good proof of viscosity reduction by adding metal particles. The optimal concentration of metal particles are critical factors to affect on viscosity reduction [8]. The objectives of this study are to clarify the potential of ZnO nanoparticles on increasing oil recovery, decreasing the residual oil saturation (SOR) and WCUT%. By considering of environmental issues and characteristics of ZnO nanoparticles, the event of viscosity reduction by adding nanoparticles causes to use lower energy to supply steam in thermal process which helps to save more energy and water.

MATERIALS AND METHODS

A 2D sand pack model was designed for studying SAGD experiment. A single SAGD process well pair structure was deployed for steam injection and oil production. The vertical spacing between well pairs, *l*, set up to 15 cm. Two experiments were conducted which the major experimental condition sand purposes are listed in Table 1.

Scaled Reservoir Model

For investigating SAGD process, a rectangular physical model (Sand pack) designed for this study which was made of stain steel 316 with dimensions 20 × 20 × 4 cm^3. As shown in Fig. 1, the physical model was consisted of different parts.

Materials

The crude oil used in this study was taken from an Iranian heavy oil field. Heavy oil properties are given in Table 2. The water phase for all experiments as base fluid was distilled water with viscosity of 1cp at ambient condition. To study the effect of nanoparticle on SAGD process, zinc oxide was selected. ZnO nanoparticles specifications are listed in Table 3.

Selection of the best concentration of nanoparticles is one of the challenging issues. Fig. 2 shows the effect of different concentrations of ZnO nanoparticles on heavy oil viscosity at different temperatures. It seems that by adding nanoparticles, viscosity reduction happens more. Another feature of Fig. 2 is that by decreasing nano concentration, viscosity decreases more. It is presumed that the main reason of this viscosity reduction can be related to the catalytic characteristics of nanoparticles on breaking the carbon and sulfur bonds in a chemical reaction. The most viscosity reduction happens at the lowest concentration of nanoparticles (0.2-0.5%wt).

Experimental Procedure

Prior to all experiments, the model was assembled. The thermocouples were placed back into the model and the pressure test was conducted. Usually the model was left pressurized with gas for

Fig. 3. Oil saturating set up; a) put the packed model inside the oven, b) fill the accumulator (600 ml) with heavy oil, c) connect the accumulator to injection pump and packed model, d) pump 2PV of heavy oil to the model to make sure it saturated with heavy oil completely.

Fig. 4. Flooding the packed model with nanoparticles; a) fill the accumulator 600 ml with homogeneous ZnO nanoparticles solution, b) connect the accumulator to injection pump and packed model, c) pump 2PV of nanoparticle and flood the model.

24h to make sure that there was no pressure leak. In the second step, the physical model was packed with sand from the reservoir. During packing, the model was vibrated and held at several different angles to make sure no gap would be left behind and a homogenous packing was created. The packing and shaking process typically took 24h. Table 4 shows the measured porosity, absolute permeability and pore volume of packed model for all experiments. The third step was to evacuate the model to remove air from the pore space. Finally, the model was connected to a vacuum pump and evacuated for 16h. The model was disconnected from the vacuum pump and kept on vacuum for couple of hours to make sure that it held the vacuum. If high vacuum was maintained, it was ready for saturating. Fig. 3 shows the packed model saturated with oil. The oil saturation of model took around 72h. After passing these steps, the packed model was ready for SAGD process.

For doing SAGD test with ZnO nanoparticles, the model preparation was achieved in a step-wise manner as follows; a) clean the physical model, b) vacuum the pore space of packed model, c) flood the ZnO nanoparticles to packed model about 72h, d) dry the packed model about 72h, e) saturate the model with heavy oil about 72h. After finishing the previous test, the packed model cleaned with toluene during 42 days and dried in oven for 7 days. Then the packed model flooded with ZnO nanoparticles. Water was selected as base fluid. By using ultrasonic device UP200S (Hielscher Ultrasonic, 200W, 24 kHz), homogeneous nanoparticles solution was made. Maintaining the homogeneous solution during the experiment was one of the most important challenging issues. ZnO Nanoparticles tend to be disposed after around 7h. To avoid this problem and assure that the nanoparticles affected on the packed model directly, nanoparticles flooding procedure applied. First, the model was vacuumed and as shown in Fig. 4, flooding procedure was applied. Hence, the cell was ready to saturate with heavy oil for 72h the same as previous test.

Fig. 5 shows a schematic of the displacement apparatus used in this study. This apparatus included a water pump, steam generator, steam accumulator, 2-D scaled sand pack model, production control mechanism and the data acquisition system. Water was injected using nitrogen pressure via water accumulator cylinder. This positive pressure pump could inject at pressure range between 150 and up to 4000 psi. Steam generator heated water with an electrical element to vaporize water and injected the steam by nitrogen pressure pump with constant pressure. A temperature controller was used to inject the hot fluid at constant temperatures. The physical model was built from stainless steel with operating pressure up to 10000 psi and operating temperatures up to 500 °C. The physical model and measurement tools placed in a thermostatic oven as shown by dotted line in Fig. 5. In each experiment, the oven temperature fixed at 75°C and the system was allowed to reach thermal equilibrium. For steam injection, pressure was set

Table 4. Properties of packed model used

Absolute permeability (D)	Porosity (%)	horizonral permeability / vertical permeability	Initial oil saturation	Initial water saturation
4.87	34	1	100%	0%

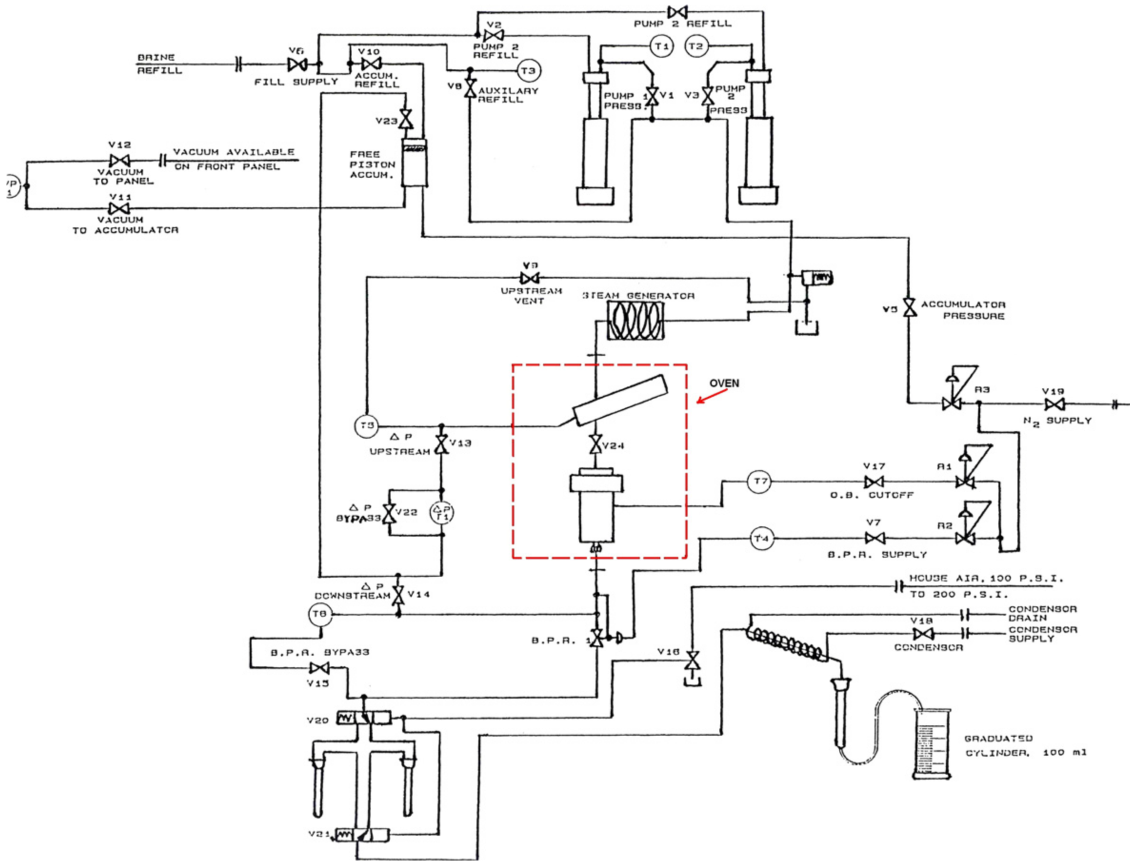

Fig. 5. Schematic representation of experimental apparatus.

in accumulator. When the system became steady state, oven and steam generation temperature and pressure injection were set and water became steam in vent tube. Once the oil production decreased below 1%, steam injection stopped. Mixture of heavy oil and produced condensate water collected in a sample bottle every 15 minutes. All oil production and condensed water measured in calibrated graduated cylindrical tubes. The oil and emulsion heated at 60 °C in the oven for 24h to break emulsion into oil and water and lately used centrifuged at 6000 RPM speed to separate the water and oil completely and the amount of separated oil was measured. The fluid cooled in a condenser before collection.

RESULTS AND DISCUSSION

The first experiment used the configuration with vertical distance between the horizontal well-pair of 15 cm. The oil recovery is shown in Fig. 6. When the injection well is at =15 cm from producer, it takes much time to invade heavy oil to start production. Despite fast creating steam chamber, improving the steam chamber domain is slow. Passing the time, more area of heavy oil heats by steam and gets mobile. As oil produces, steam chamber is able to touch and transfer heat to wider area of oil. Meanwhile, steam chamber effect is sensible and oil production increases. The steam breakthrough happens after 53 minutes. The ultimate oil recovery is 52.43% after 690 minutes. Obviously, locating

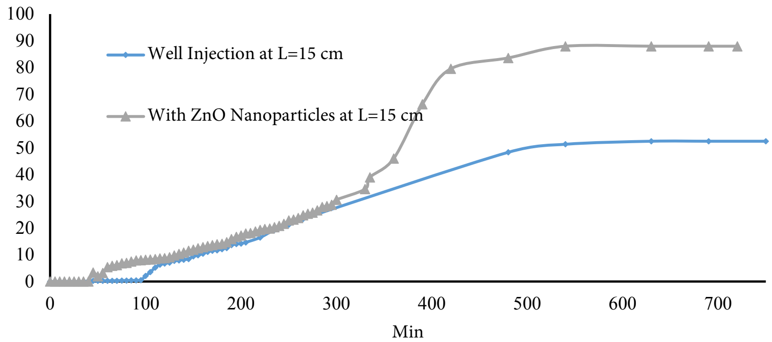

Fig. 6. Oil recovery for two sets of experimental conditions.

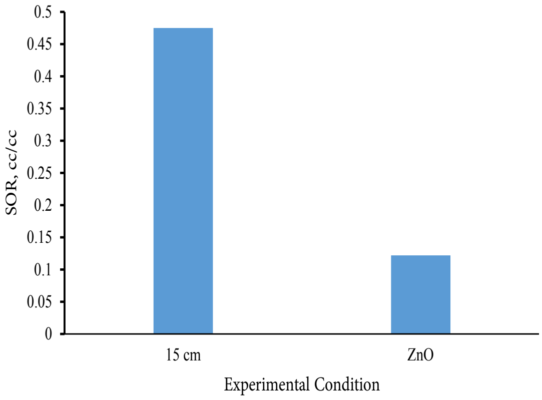

Fig. 7. SOR for well distance at well distance at 15 cm and with ZnO nanoparticles.

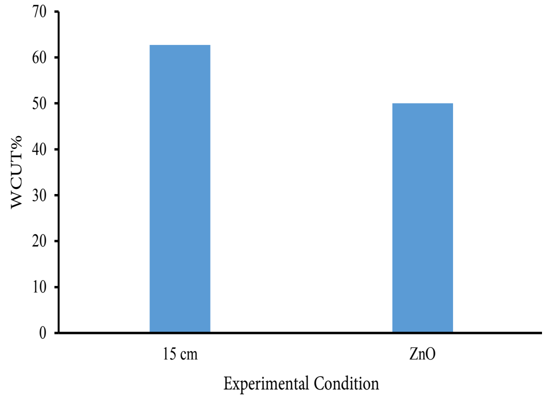

Fig. 8. WCUT% for two steps of experimental conditions; well distance at 15 cm and with ZnO nanoparticles.

well injection at 15cm causes more area of heavy oil is invaded by steam chamber heat therefore, experiment's time is longer and oil production increases more. Considering the findings from previous experiments in second experiment, the oil recovery is shown in Fig. 6. The condition of steam chamber formation is almost the same as previous experiment. After 62 minutes, the steam breakthrough happens. The role of nanoparticles becomes important once steam adds to the system. Nanoparticles have very small particle sizes which penetrate into pore volume of porous media and stick on the packed model surface. As shown in Fig. 2, by increasing the heavy oil temperature and ZnO nanoparticles, viscosity reduces dramatically. This feature of ZnO nanoparticles together with steam injection helps to intensify heavy oil viscosity reduction. It is clear from Fig. 6, the effect of ZnO nanoparticles on decreasing oil viscosity is sensible which helps to raise oil recovery compared to previous experiment. Another interesting finding is that ZnO nanoparticles causes the experiment time shorter with high oil recovery. The ultimate oil recovery is 87.93% of OOIP at 630 minutes of experiment thanks to ZnO nanoparticles.

SOR for two experiments is shown in Fig. 7. It can be seen that, SOR for the first experiment (l=10 cm) is roughly 1.3 higher than second experiment (l=15 cm). Larger well spacing has considerable effect on SOR reduction. The important role of ZnO nanoparticles is clear for SOR reduction. As shown, SOR for second experiment is 3.89 higher than SOR of experiment with ZnO nanoparticles.

The comparison of WCUT% for two experiments also confirm that ZnO nanoparticles have potential to decrease the water content about 1.25 times than the second experiment and 1.6 times compared to the first experiment. The results of water cut for each experiment are shown in Fig. 8.

Due to increasing demand on fresh water sources, saving energy through improved efficiency and conservation by adding nanoparticles has a central role to play in reconciling the goals of economic development, energy security and environmental protection. Producers will need to understand their water demands, not just to improve the yield of their wells, but also to address the growing public concern over fracking. In particular fresh water resources which may already be fully allocated and wastewater storage and disposal can become hot-button issues with local communities. As shown in Fig. 8 the use of nanoparticles will be increasingly used to prevent wastewater fouling. As a result, oil companies are fast at work making their activities less water intensive. Hence, nanotechnology can help oil industry in this issue.

CONCLUSIONS

Oil and gas producers need to understand their water consumption, the requirements and limitations of the areas in which they operate and the potential of nanotechnology investment to protect and enhance their profitability into the future. This study shows the capability of ZnO nanoparticles to reduce viscosity and increases heavy oil recovery whereas WCUT% is decreased through SAGD process. The catalytic chemical reaction of nanoparticles on breaking the bonds between carbon and sulfur is assumed that the main reason of viscosity reduction. The most viscosity reduction happens at the lowest concentration of nanoparticles (0.2-0.5%wt). Based on ZnO nanoparticles characteristics on viscosity reduction, the final oil recovery is considerably increased hence, the SOR and WCUT% is definitely decreased.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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