Research Article

Experimental and Numerical Studies of Supercritical Water Flooding for Offshore Heavy Oil Recovery

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Received 1 June 2021; Accepted 3 May 2022; Published 23 May 2022

Academic Editor: Bailu Teng

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Supercritical water (SCW) is a novel thermal agent that has been recently utilized for the production of heavy oil. However, a lack of knowledge about its recovery mechanisms limits the application of SCW. In this study, pyrolysis and sandpack flooding experiments were performed to investigate the mechanisms and viability of SCW flooding. Then an innovative simulation model was developed for SCW flooding. Finally, sensitivity studies on SCW flooding were conducted by the developed model. The results showed that SCW flooding yielded a 13.99% increase in oil recovery in comparison to steam flooding, indicating that SCW flooding is technically applicable to offshore heavy oil reservoirs. Heavy oil upgrading in SCW can suppress coke formation and plays an important role in oil recovery. A novel numerical model for SCW flooding was established based on a history match of experiments. The simulation results suggested that during SCW flooding, SCW could induce heavy oil upgrading to increase oil mobility, and long-term injection of SCW may cause the formation of coke deposits. Higher injection temperatures and pressures would benefit the production performance of SCW flooding. However, an unlimited increase in temperature would damage formations by significant coke deposits.

1. Introduction

Recently, limited light oil resources have been gradually exhausted worldwide. Therefore, petroleum engineers have turned their attention to heavy oil resources [1–6]. Due to the low but temperature-sensitive mobility of heavy oil, various thermal methods, including hot water flooding, cyclic steam, or multithermal fluid stimulation and steam flooding, are normally applied to recover heavy oil [7–10]. However, due to heat losses and low steam quality during steam or multithermal fluid injection and extremely low water-oil mobility ratios during hot water injection, the aforementioned methods are inefficient for offshore heavy oil reservoirs. This situation has motivated researchers to find novel agents that can be used to extract heavy oil from deep offshore reservoirs.

The supercritical state of water can be realized when the temperature and pressure are greater than the critical values (647 K and 22.1 MPa, respectively) [11]. As a special phase of water, SCW presents the advantages of both steam and liquid water. It can diffuse as steam at high pressure, act as a reaction medium, and improve reaction kinetics by dissolving organic compounds [12, 13], and it has high heat efficiency. Due to these favorable properties, SCW shows promise for applications in the field related to heavy oil recovery.

For example, Morimoto et al. found that SCW could inhibit coke formation and increase the recovery of light fractions [14]. Zhao et al. studied the viability of heavy oil upgrading in SCW and reported that the upgraded oil had a 95% reduction in viscosity relative to the original feedstock [15]. Recently, some studies were conducted to investigate
2. Pyrolysis Experiments

2.1. Materials. Heavy oil supplied by the Bohai oil field, China, was used as feedstock. The density and average molecular weight of the heavy oil at 50°C were 985 kg/m³ and 750 [18], respectively, and the viscosity-temperature curve of the heavy oil is shown in Figure 1. Deionized water was prepared for the reaction. Toluene with 99% purity for separation of the pyrolysis products was produced by Shanghai Titan Scientific Co., Ltd, China.

2.2. Experimental Apparatus and Procedure

2.2.1. Pyrolysis Experimental Procedure. The pyrolysis experiments were conducted in an autoclave that could withstand 450°C and 35 MPa. A detailed description of the reactor can be found in an earlier publication [18].

The heavy oil was loaded with double the mass of water in the autoclave. The reactor was sealed, and argon was then utilized to purify the experimental apparatus. The reactor was heated at a rate of 10°C/min in an electric furnace to reach the desired temperatures. The stirring rate was kept at 800 rpm during the reaction, and a circulating water bath was employed to protect the stirrer from damage. After 2 h, the pyrolysis reaction was quenched with cold water. The gas product was first collected in a gas collector, and then the autoclave was thoroughly washed with toluene to obtain the rest of the product. The conditions of the two experiments were 340°C and 10 MPa (steam) and 380°C and 23 MPa (SCW).

2.2.2. Analytical Procedures. The oil product and coke were separated by filtration, and their masses were measured by an analytical balance. The yields of coke, oil products (Y_i), and gas product (Y_g) were calculated using the following equations:

\[ Y_i = \frac{m_i}{m} \times 100\%, \]

\[ Y_g = 100\% - \sum Y_i, \]

where \( m \) denotes the mass of the heavy oil and \( m_i \) denotes the mass of oil products or coke. The viscosity, density, and molecular weight of the oil product at 50°C were tested according to PRC National Standard GB/T 265-1988, PRC National Standard GB/T 2013-2010, and PRC National Standard GB/T 8107-2012, and the composition of the gas product was detected by a Bruker GC-450 gas chromatograph.

2.3. Experimental Results. The results of the pyrolysis experiments are shown in Figures 2 and 3. After pyrolysis in SCW, the viscosity, density, and molecular weight of the heavy oil were significantly reduced by 94.49%, 6.19%, and 44.27%, respectively (Figure 2(a)), whereas the corresponding reductions after pyrolysis in steam were only 15.13%, 0.71%, and 6.80%. These results indicated that pyrolysis was much more efficient for improving oil mobility under the SCW environment than under the steam environment.

In addition, as exhibited in Figure 2(b), compared with pyrolysis in steam, pyrolysis in SCW yielded more gas product (7.55% in SCW and 1.86% in steam), and the analysis of the gas products showed that the proportion of light gas fractions (C1-C3) increased from 63.33% to 72.86% when heavy oil upgrading was transferred from the steam to the SCW environment (Figure 3). The drastic increases in gas product yield and light gas fractions suggested that the heavy oil upgrading under the SCW atmosphere underwent an accelerated dealkylation process and generated more light oil fractions, thus decreasing the density, viscosity, and molecular weight of the heavy oil.

Coke formation (Figure 2(b)) indicated the occurrence of condensation during both pyrolysis processes. The two experiments produced similar yields of coke (0.16% in
SCW and 0.14% in steam). For common pyrolysis, increasing the temperature can significantly accelerate the condensation reaction, which substantially increases the coke yield. The similar coke yields of the pyrolysis processes under SCW (380°C) and steam (340°C) environments indicated that the presence of SCW can suppress coke formation. The reason for the aforementioned behavior is that SCW can dissolve and disperse heavy oil fractions, which is unfavorable for coke formation.

In conclusion, the use of SCW is more efficient than steam in terms of the upgrading of heavy oil, which plays an important role and should be considered in simulations of SCW injection.

3. Sandpack Flooding Experiments

3.1. Experimental Setup and Procedure. A new sandpack flooding apparatus was developed to conduct steam and SCW flooding tests under reservoir conditions. The setup of the experiments is shown in Figure 4. The apparatus mainly consisted of an SCW generator, a precise high-pressure pump, a model sandpack, a vacuum system pump, a computer, a cooling system, a backpressure regulator (BPR), and cylinders.

The SCW generator was produced by YH Petroleum Machinery Technology Co., Ltd, China. It could generate SCW at temperatures and pressures up to 450°C and 35 MPa. A precise high-pressure pump was connected to an SCW generator to introduce distilled water. This pump was also applied to inject heavy oil and formation water (5 wt% NaCl) into the sandpack model from two cylinders.

As illustrated in Figure 4, a novel one-dimensional sandpack model with a diameter of 38 mm and a length of 480 mm was employed to simulate a reservoir. The model could resist extreme pressures and temperatures (up to 35 MPa and 450°C). It was equipped with six band heaters and an insulation jacket to maintain the temperature and reduce heat losses. In addition, 16 temperature sensors were uniformly arranged along the model, and 2 pressure sensors were set at the inlet and the outlet. The data obtained by the sensors was recorded by the computer.

The injection and model pressures were adjusted by the BPR. The produced liquid was cooled by a condenser connected to a water bath, and the volume of liquid was measured by a graduated cylinder.

A systematic methodology was used to conduct the flooding experiments. First, the sandpack was packed with silica sands (grain size of 150-250 μm), and then it underwent a leakage test and vacuum step. Then, the sand pack was saturated with formation water, the porosity was determined through the volume method, and the permeability was tested according to Darcy’s law. Afterward, the sand pack was saturated with oil (the heavy oil described in Section 2) under offshore reservoir conditions (50°C and 10 MPa). The porosity, permeability, and initial oil saturation were 0.56, 5630 mD, and 0.96 in the steam flooding conditions.
Figure 4: Schematic diagram of the experimental apparatus.

Figure 5: Experimental results of steam and SCW flooding: (a) oil recovery, (b) pressure difference, (c) inlet and outlet cross-sections, and (d) temperature distributions.
and 0.55, 5467 mD, and 0.94 in the SCW flooding, respectively. After the preparation of the sandpack, steam and SCW flooding were conducted at the same injection rate of 10 ml/min but at different temperatures and pressures (i.e., 340°C and 10 MPa for steam and 380°C and 23 MPa for SCW).

3.2. Experimental Results. The results are displayed in Figure 5. Figure 5(a) shows that SCW flooding yielded an oil recovery of 70.54%, which was 13.99% greater than the result of steam flooding. Figure 5(c) indicates that the residual oil saturation was lower for SCW flooding than steam flooding. In conclusion, SCW flooding is technically applicable to offshore heavy oil reservoirs.

The coke (black spots) distributed at the inlet and outlet (Figure 5(c)) suggested the occurrence of heavy oil upgrading during the flooding process. As explained in the previous section, the reduction in oil viscosity during heavy oil upgrading was more drastic in the presence of SCW than steam. In addition, as presented in the temperature distributions (Figure 5(d)), the sandpack temperature was higher (causing a greater decrease in oil viscosity) during SCW flooding than during steam flooding. These factors contributed to improved oil mobility during SCW flooding in comparison to steam flooding.

Moreover, Figure 5(b) shows that the pressure difference was greater and has a longer duration for SCW flooding than steam flooding, and the promotion of SCW was more uniform (Figure 5(d)), indicating that the SCW breakthrough was restrained in contrast to that of steam. One possible reason for this behavior should be ascribed to the higher density of SCW compared with steam [12]. The other reason is that SCW could be miscible with heavy oil, thus significantly reducing the oil-water interfacial tension. The aforementioned reasons caused the suppressed override during SCW flooding in contrast to steam flooding.

4. Numerical Simulations

4.1. Numerical Approach. The numerical simulations of SCW flooding were conducted by using the STARS simulator in the CMG software (Computer Modelling Group (CMG) Ltd., Canada). Based on the flooding experiments, a laboratory-scale simulation model was established with

![Figure 6: The laboratory-scale model.](image)

![Figure 7: Oil-water and gas-liquid relative permeability: (a) oil-water relative permeability and (b) gas-liquid relative permeability.](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<td>Injection temperature, °C</td>
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<td>Fluid injection rate, ml/min</td>
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<td>Water phase thermal conductivity, J/(m³·d·°C)</td>
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<td>Oil phase thermal conductivity, J/(m³·d·°C)</td>
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<tr>
<td>Gas phase thermal conductivity, J/(m³·d·°C)</td>
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a 48 × 19 × 19 grid system (grid dimensions of 2.0 cm × 0.2 cm × 0.2 cm) as shown in Figure 6.

In this model, 4 phases (i.e., aqueous, oleic, gaseous, and solid phases) and 5 components (i.e., water, heavy oil, light oil, gas, and coke) were defined. According to the oil property tests, product distribution, and gas product analysis presented in Section 2, the chemical reaction shown in the following equation was applied to describe heavy oil upgrading during SCW flooding.

\[
20 \text{ mol SCW} + 1 \text{ mol heavy oil} = 20 \text{ mol water} + 1.43 \text{ mol gas product} + 1.68 \text{ mol light oil} + 0.001 \text{ mol coke}
\] (3)

The relative permeability curves for the Bohai heavy oil are illustrated in Figure 7.

The key properties and operational parameters for the simulations are shown in Table 1.

4.2 Model Verification. The uncertain parameters of the model, such as the relative permeability, frequency factor, and activation energy, were determined through a history matching of oil recovery, pressure difference, and temperature distributions. In particular, the frequency factor and activation energy are the main parameters for representing the pyrolysis reaction process during SCW flooding. To accurately simulate heavy oil pyrolysis during SCW flooding, reasonable tuning ranges of the frequency factor and activation energy were obtained from the literature and are shown in Table 2. As shown, the tuning ranges of the activation energy and the frequency factor were 189.60-272.30 kJ/mol and 3.50 × 10^{18} – 5.18 × 10^{19} min^{-1}, respectively. The final values of the two parameters were then determined based on the history matching of the flooding experimental results.
According to the results of the fit, the frequency factor and activation energy were $5.50 \times 10^{18}$ min$^{-1}$ and 253 kJ/mol, respectively.

As illustrated in Figure 8(a), the numerical model reproduced the experimental oil recovery results with an average deviation of 4.11%.

In addition, the temperature distribution and pressure difference results (Figures 8(b) and (c)) showed that the results of the simulation were in good agreement with the results of the experiment, confirming that the simulation model can accurately simulate the dynamics of SCW flooding.

4.3. SCW Flooding Analysis. The numerical simulation was conducted by using the developed model after the match with historical records to further analyze SCW flooding processes. The inaccessible parameters for the SCW flooding experiment, such as the spatial distributions of oil viscosity, oil saturation, coke concentrations, and mole fractions of SCW, gas, and light oil, were determined based on the simulation studies (Figure 9).

At an injection volume of 0.5 PV, the SCW mainly accumulated near the inlet, leading to a small swept zone (Figure 9(a)). Therefore, the oil viscosity of the whole model was high (Figure 9(c)), resulting in a small amount of displaced heavy oil (Figure 9(b)). As flooding proceeded, the constant injection of SCW led to a rapid promotion of the heat area at 1.5 PV, which can be justified by the increase in the SCW mole fraction (Figure 9(a)). The advance of the SCW front was relatively uniform. Due to the high temperature and deep heavy oil upgrading characterized by increases in the mole fractions of gas light oil and the coke concentrations (Figures 9(d)–9(f)), the oil viscosity (Figures 9(b) and 9(c)) in the swept zone significantly decreased, drastically reducing the oil saturation. As the injection volume reached 2.5 PV, the whole model was heated to 380°C, and a stable flow channel formed (Figure 9(a)), suggesting the appearance of a breakthrough at this stage. As a consequence, the oil could not be efficiently extracted from the model (Figure 9(b)). The average residual oil saturation was 25.62% at the end of the simulation (4 PV), suggesting that SCW flooding can efficiently recover offshore heavy oil.
Notably, the coke concentrations gradually increased as SCW flooding continued, indicating that the injection of SCW resulted in coke formation, especially near the inlet region (Figure 9(f)). However, the maximum coke concentration in the model was only $2.26 \times 10^{-6} \text{kg/cm}^3$, which was relatively low. The possible reason is that coke formation was suppressed due to the presence of SCW, which would be consistent with the results of the pyrolysis experiments.

4.4. Sensitivity Studies of the SCW Flooding Processes

4.4.1. The Effect of Injection Temperature. Figure 10 shows the oil recovery, oil production rate, average oil viscosity, oil saturation, mole fraction of light oil, and coke concentration at different injection temperatures, viz. 380°C, 390°C, 400°C, 410°C, and 420°C.

As shown in Figure 10(a), the oil recovery increased significantly from 70.26% to 80.50% with variation in temperature from 380°C to 420°C. In addition, with increasing injection temperature, the oil production rate (Figure 10(b)) and average mole fraction of light oil (Figure 10(d)) increased significantly, and the average oil viscosity and oil saturation (Figure 10(c)) considerably decreased. These results indicated that the increase in SCW injection temperature favored heavy oil recovery, which should be ascribed to two reasons. First, the higher injection temperature favors heat transmission, suggesting a more rapid expansion of the heat area. Second, the rising temperature could accelerate the pyrolysis reaction, which also contributes to the increase in heavy oil mobility. However, the increase in injection temperature resulted in significantly enhanced coke formation (Figure 10(d)). This should be attributed to the higher upgrading degree induced by the higher injection temperature, indicating that a drastic rise in the SCW injection temperature would lead to damage of the formation by enhanced deposition of fine particles.
4.4.2. The Effect of Injection Pressure. Different injection pressures (23 MPa, 24 MPa, 25 MPa, 26 MPa, and 27 MPa) were assigned to study their effects on SCW flooding. The simulation results are displayed in Figure 11. As presented in Figure 11(a), the oil recovery increased from 70.26% to 74.86% as the injection pressure rose from 23 MPa to 27 MPa.

As shown in Figures 11(b)–11(d), SCW flooding at higher injection pressures achieved higher oil production rates, higher light oil fractions, lower oil saturations, and slightly higher coke concentrations. It can be concluded that the production performance of SCW flooding was enhanced by increasing injection pressure. The reason for the better performance at high pressures was attributed to the fact that the rising pressure caused a notable increase in the SCW density and the solubility of hydrocarbons [15], which effectively mitigated the SCW override. Moreover, the elevation of injection pressures was beneficial for decreasing oil viscosity through enhanced heavy oil upgrading in SCW [24].

5. Discussion of the Potential Application of the SCW Flooding Process in Oil Fields

The experimental and simulation studies confirmed that SCW flooding is capable of recovering offshore heavy oil and revealed the mechanism of this technique. Therefore, this paper discusses the potential of SCW flooding in applications in oil fields.

(1) The main challenges that may hinder the usage of SCW flooding are the extremely high material requirements for the generator and injection systems, possible high fuel cost, and large volumes of greenhouse gas emissions. Recently, Zhou et al. proposed a novel design for generators and injection systems that can withstand the high temperature and pressure of SCW [25]. According to their patent, SCW was generated by the gasification and combustion of organic waste, suggesting a limited fuel cost. All the products would be injected into
the reservoir, indicating no emissions of greenhouse gases. In addition, due to the small volume of the innovative SCW generator, the SCW flooding equipment is not only applicable to onshore sites but also quite suitable for offshore platforms with limited space. Therefore, it is inferred that the application of SCW flooding can be technically viable, energy-saving, environmentally friendly, and extensive.

(2) Injected water could not be maintained in a supercritical state in shallow formations where there are low reservoir pressures, suggesting that SCW flooding is not applicable to shallow heavy oil reservoirs. In contrast, due to the high injection temperature, great diffusivity [11], and significant effect on improving mobility through pyrolysis and extraction (as described above) under high pressure, SCW flooding is of great benefit for developing deep onshore and offshore heavy oil reservoirs. In fact, the application of SCW injection in the Lukeqin oil field (with an average reservoir depth of more than 2000 m) showed promising results (increased cyclic oil production of two wells by 640 t per cycle in comparison to steam stimulation) [16], indicating excellent prospects for applications of SCW flooding for extracting heavy oil from deep onshore and offshore reservoirs.

(3) In addition, thermal recovery assisted by noncondensible gas and solvent injection was proven to be an efficient technique to enhance heavy oil recovery [26, 27]. Thus, during future practical applications, the addition of noncondensible gases and solvents may be a feasible method to improve the performance of SCW flooding.

However, the application of SCW flooding in oil fields is still undergoing assessment. To understand its proper application including economic and environmental feasibility, extensive research is ongoing.

6. Conclusions

(1) The experimental results for the pyrolysis of heavy oil illustrated that compared to steam, SCW can significantly reduce the viscosity, density, and molecular weight of oil by 5.89%, 94.33%, and 43.60%, respectively, and suppress coke formation. Heavy oil upgrading plays an important role during SCW flooding.

(2) The results of sandpack flooding experiments showed that, in contrast to steam flooding, SCW flooding resulted in a substantial 13.99% increase in oil recovery. This indicated that SCW flooding is feasible for heavy oil recovery from offshore reservoirs. Significant heavy oil upgrading and override suppression are the main recovery mechanisms of SCW flooding.

(3) An innovative simulation model was developed based on the pyrolysis and flooding experiments, and it was proven to accurately simulate SCW flooding.

(4) SCW gradually promoted from the inlet to the outlet during the continuous injection. The injected SCW induced heavy oil upgrading, which played an important role in the reduction of oil viscosity. The SCW could not displace heavy oil after it broke through. In addition, long-term injection of SCW might cause the formation of coke deposits, which would block the injection area.

(5) Elevated temperatures favored heavy oil production. However, an unlimited increase in injection temperature could result in a formation damage. Accordingly, a moderate SCW injection temperature should be adopted during practical applications.

(6) Increasing the injection pressure can suppress SCW override and intensify heavy oil upgrading. Thus, the SCW injection pressure should be increased to the upper limit of the offshore oil field equipment.

(7) The application of SCW flooding can be technically viable, energy-saving, environmentally friendly, and extensive. SCW flooding is applicable to extracting heavy oil from deep onshore and offshore formations. The addition of noncondensible gases and solvents may be a feasible method to improve the performance of SCW flooding during future practical applications. However, further research should be conducted to determine the economic and environmental feasibility of SCW flooding.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the Open Fund of State Key Laboratory of Offshore Oil Exploitation (Project No: CCL2018RCP00017RON).

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