

Article

Cyclic Supercritical Multi-Thermal Fluid Stimulation Process: A Novel Improved-Oil-Recovery Technique for Offshore Heavy Oil Reservoir

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Abstract: Cyclic supercritical multi-thermal fluid stimulation (CSMTFS) is a novel technology that can efficiently recover heavy oil, while the heating effect, production and heat loss characteristics of CSMTFS have not been discussed. In this study, a physical simulation experiment of CSMTFS is conducted with a three-dimensional experimental system. The results of the study indicate that the whole process of CSMTFS can be divided into four stages, namely, the preheating stage, production increase stage, production stable stage and production decline stage, of which the production stable stage is the main oil production stage, and the production decline stage is the secondary oil production stage. In the first two stages of the CSMTFS process, there is no supercritical multi-thermal fluid chamber, and only a relatively small supercritical multi-thermal fluid chamber is formed in the last stage of the CSMTFS process. Out of the supercritical multi-thermal fluid chamber, supercritical water in the thermal fluids condensates to hot water and flows downward to heat the subjacent oil layer. At the same time, the non-condensate gas in the thermal fluids accumulates to the upper part of the oil layer and reduces heat loss. The analysis of heat loss shows that the heat loss rate gradually increases at first and then tends to be stable. Compared with conventional thermal fluid, the CSMTFS can more effectively reduce heat loss. The enthalpy value of supercritical multi-thermal fluid is significantly increased compared with that of multi-thermal fluid, which effectively solves the problem of insufficient heat carrying capacity of multi-thermal fluid. Overall, cyclic supercritical multi-thermal fluid stimulation can effectively solve the problems of conventional heavy oil thermal recovery technology in offshore heavy oil recovery; it is indeed a new improved-oil-recovery technique for offshore heavy oil. The findings of this study can help in better understanding the cyclic supercritical multi-thermal fluid stimulation process. This study is significant and helpful for application of CSMTFS technology in heavy oil recovery.

Keywords: heavy oil; physical simulation; supercritical multi-thermal fluid



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1. Introduction

Heavy oil resources are abundant in the world, and their reserves are no less than conventional crude oil resources [1–6]. China is rich in heavy oil resources, and a large number of heavy oil resources are concentrated in the Bohai Bay. Due to the limitations of offshore platforms, conventional thermal recovery technologies (such as steam flooding, steam huff and puff, and conventional multi-thermal fluid) struggle to achieve good results at sea [7–11], which leads to a low degree of utilization of offshore heavy oil in China. Considering this situation, Zhou et al. [12] creatively combined supercritical water technology with heavy oil thermal recovery technology and proposed supercritical multi-component thermal fluid (SMTF) technology; that is, supercritical water reacts with diesel oil, heavy oil or oily sewage to generate supercritical multi-thermal fluid for offshore heavy oil thermal recovery. The main components of supercritical multi-thermal fluid include

supercritical water, nitrogen and carbon dioxide, which are characterized by large heat carrying capacity, strong solubility and good diffusion.

Cyclic supercritical multi-thermal fluid stimulation (CSMTFS) is a specific form of supercritical multi-thermal fluid applied to heavy oil thermal recovery. The use of supercritical multi-thermal fluid for huff and puff development of offshore heavy oil can effectively overcome the problems existing in the offshore application of conventional thermal recovery technology, such as large heat loss, high dependence on fresh water and diesel oil, and high maintenance cost of complex pipelines. It is expected to improve the development effect of offshore heavy oil while reducing costs.

After supercritical multi-thermal fluid was proposed, many scholars paid attention to its generation process. Their studies [12–14] demonstrated through experiments that the generation process of supercritical multi-thermal fluid should be divided into two stages. First, supercritical water uses its own strong dissolution capacity to dissolve and disperse the organic substances in the reactants, and then, with the participation of oxygen, these organic substances are completely oxidized and decomposed in the supercritical water environment. These decomposed products, together with supercritical water, are called supercritical multi-component thermal fluids.

Subsequently, the interest of scholars was gradually attracted to the question of how to use supercritical multi-thermal fluid and its mechanism of heavy oil recovery; some research has focused on CMTFS. As the supercritical multi-thermal fluid also contains a large amount of nitrogen and carbon dioxide, the existing research on conventional thermal recovery technology also has certain reference value. Previous studies have confirmed that the addition of N_2 , CO_2 and other non-condensable gases during the steam stimulation procedure can improve the steam stimulation recovery effect of heavy oil efficiently [15–18]. The results showed that, besides reducing viscosity by heating, multi-thermal fluid (MTF) also reduces viscosity by dissolving non-condensable gas (mainly CO_2) [19–23]. Moreover, the non-condensable gas (mainly) N_2 can also reduce the heat loss of the reservoir and maintain the reservoir pressure, thereby improving the recovery factor [24–29].

As the main component of supercritical multi-thermal fluid, supercritical water was once a great concern of scholars. These scholars successively carried out a series of research studies, which laid a foundation for the research of supercritical multi-thermal fluid. A deep heavy oil reservoir in northwest China took the lead in field testing of supercritical water huff and puff [30], and the production data showed that its recovery effect was improved compared with the conventional cyclic steam stimulation (CSS). On the basis of this study, scholars have carried out some research. Some studies discussed the process and characteristics of heavy oil recovery by supercritical water huff and puff technology through experimental research and theoretical analysis [31,32]. Some scholars focused on the supercritical hydrothermal cracking process of heavy oil, and discussed the reaction characteristics of the cracking process [33,34]. The results of these studies confirm that supercritical water can decompose macromolecular hydrocarbons in heavy oil into small molecule hydrocarbons and coke. With the gradual deepening of the research, the research on the mechanism of enhancing heavy oil recovery by supercritical water gradually emerged [35–38], among which [36] even started to conduct numerical simulation of this process.

However, as a new technology, although it has been gradually noticed by scholars, there is no research on the recovery effect and production characteristics of CSMTFS. In view of this situation, the L oil reservoir in Bohai was taken as the research object in this study, and a three-dimensional physical simulation experiment of CSMTFS was conducted by using a high temperature and high pressure model. During the experiment, the temperature and pressure distribution of the model and the production data of each cycle were obtained. With the results, heating effect, heat loss and production characteristics of CSMTFS were evaluated and analyzed. The issues discussed in this study are significant for a comprehensive understanding of the typical production characteristics of CSMTFS, and it can be used as a reference for CSMTFS oilfield practice.

2. Materials and Methods

2.1. Apparatus

The experimental apparatus consists of three main parts: injection–production system, reservoir model system and monitoring system, as shown in Figure 1. The injection–production system mainly includes distilled water, ISCO pumps, supercritical water generators (steam generators), non-condensable gas cylinders, pressurization pump, intermediate containers, hand pump and test tubes. The reservoir model system is a cube sand filling experimental device (Figure 2); the internal size of the model is 400 mm × 400 mm × 400 mm. The maximum working pressure of the model is 30 MPa and the maximum working temperature is 450 °C; the monitoring system mainly includes temperature sensors, pressure sensors, a data acquisition module and a computer.

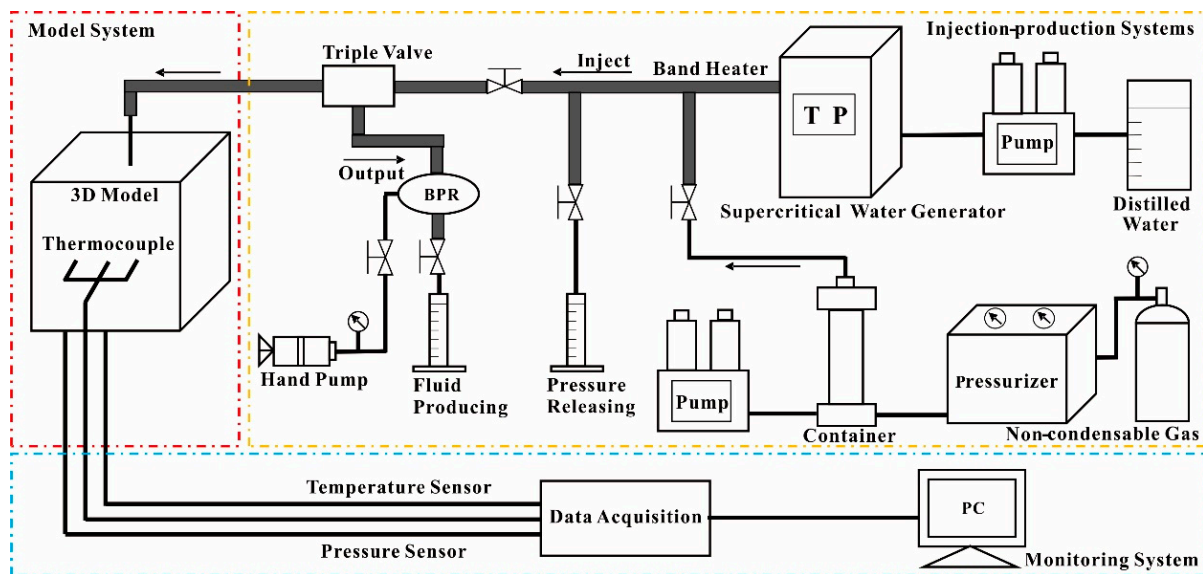


Figure 1. Flow diagram of three-dimensional physical simulation experiment.



Figure 2. Three-dimensional physical model.

As shown in Figure 3, the three-dimensional physical model is divided into 3 layers. A model well is placed vertically in the center of the oil layer, and the bottom of the well is 300 mm from the top of the model. Part of the wellbore in the middle sand layer is perforated. A total of 46 thermocouples are placed in the top layer and oil layer, and have

the same distribution in both of them. Eight pressure probes are placed in the middle of the oil layer.

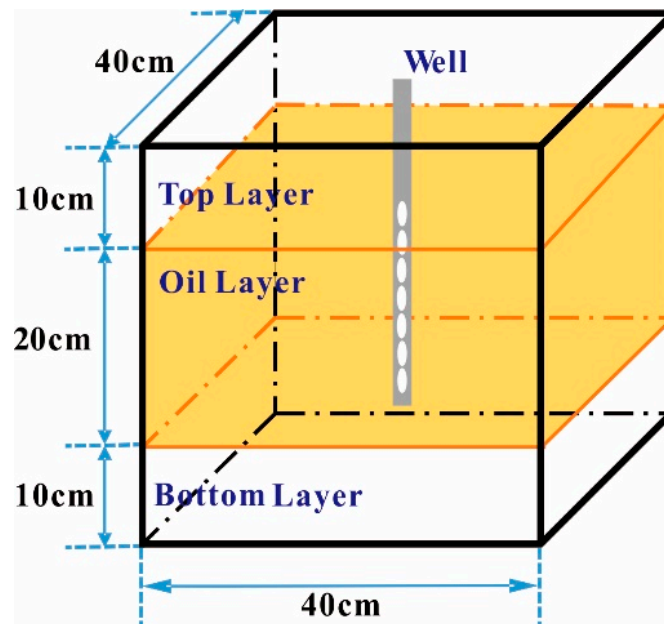


Figure 3. Schematic diagram of three-dimensional physical model.

2.2. Model Parameters

The similarity between the model and oilfield should be considered in three-dimensional physical simulation. On the basis of experimental conditions, the experimental parameters of the three-dimensional physical simulation were determined by using the scaling criteria (Table 1) before the experiment.

Table 1. Scaling criteria.

Scaling Criteria	Physical Meaning	Modeling Parameters
$\pi_1 = \frac{Kg\Delta\rho}{v\mu_o}$	Ratio of gravity to viscous force	Permeability
$\pi_2 = \frac{\alpha_o}{vL}$	The ratio of heat conduction to convection	Steam injection rate
$\pi_3 = \frac{K\Delta p}{vL\mu_w}$	Ratio of driving force to viscous force	Differential pressure
$\pi_4 = \frac{v^t}{L}$	Flow scale and space scale ratio	Time
$\pi_5 = \frac{\rho_g v_g}{\rho_s v_s}$	Ratio of mass fluidity of non-condensable gas to steam	Gas injection rate

Considering that the effective thickness of the oil layer in the L reservoir is about 40 m, while the thickness of the reservoir is designed to be 0.2 m based on the inner size of the experimental device, the geometrically similar ratio R can be obtained.

$$R = \frac{L_{\text{mod}}}{L_{\text{prot}}} = \frac{0.2}{40} = \frac{1}{200} \quad (1)$$

The crude oil used in this experiment was taken from the L reservoir and had been dehydrated and filtered before the experiment. The quartz sand used in the model has the same petro-physical properties as the L reservoir. Therefore, in the calculation process of experimental parameters, since the physical properties of the fluid and sand used in the experiment were the same as in the actual reservoir, the similarity ratio of the following parameters could be determined firstly: fluid density, fluid viscosity, oil saturation, porosity, initial reservoir temperature and initial reservoir pressure were all taken as 1. According to

the scaling criteria, the experimental parameters of the three-dimensional physical model were determined, as shown in Table 2.

Table 2. Parameter conversion of oil reservoir prototype and scale model.

Parameter	Prototype	Model
Oil layer thickness, m	40	0.2
Porosity, %	40	40
Oil saturation, %	70	70
Permeability, mD	3500	700,000
Crude oil viscosity at 50 °C, mPa·s	4759	4759
Reservoir temperature, °C	50	50
Initial formation pressure, MPa	22	22
Steam injection rate (cold water equivalent), m ³ /d	80	0.058
Cyclic cumulative steam injection volume (cold water equivalent), m ³	1600	0.0002
Cyclic injection increase, %	10	10
Soaking time, d	4	1/1440

Due to the limited experimental conditions of the laboratory, the steam injection rate directly converted according to the scaling criteria could not be satisfied, so it was necessary to determine a reasonable steam injection rate according to the experimental conditions. Considering the working conditions of the injection pump in the laboratory, the steam injection rate was designed to be 40 mL/min. At the same time, based on the cyclic cumulative steam injection volume and injection time, it could be calculated that 5 min of model injection was equivalent to 20 days of reservoir injection time, which meant that 1 year of reservoir recovery was equivalent to 82.5 min of model operation.

2.3. Procedures

Before the experiment begins, prepare the oil sample and sand required for the experiment, and then check the experimental apparatus to ensure that they can be operated normally. After that, connect the apparatus according to the experimental flow diagram (Figure 1).

(1) Load the model. Prepare the bottom layer with mud, and then fill the model with oil sands; during this process, place well, temperature and pressure measurement sensors in the predetermined position, as shown in Figure 4. After that, prepare the top layer.

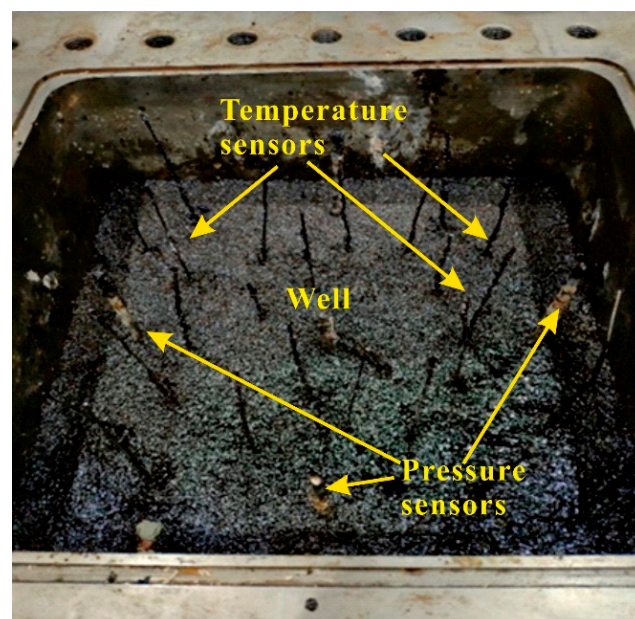


Figure 4. Process of filling the three-dimensional physical model.

(2) Model initialization. After the loading process, check the hermeticity of the model. Then, move the model into the air bath. When the inner temperature of the model reaches 80 °C, saturate the crude oil into the model with a low flow rate to make the model pressure reach the predetermined pressure. Then, set the temperature of the air bath to 50 °C and age the model for no less than 48 h to simulate the initial state of the actual reservoir.

(3) Steam generator initialization. Before the SMTF is injected into the model, the steam generator should be heated and pressurized to make the injection temperature and injection pressure reach the predetermined values (390 °C, 22.1 MPa). At the same time, turn on the electric heating belt to preheat the steam injection pipeline.

(4) Experimental operation. During the experiment, the monitoring system records the temperature and pressure of the model, while the injection–production system injects SMTF into the model and collects the produced fluid in different cycles. The experiment ends when the predetermined maximum cycle is reached.

2.4. Methods

2.4.1. Analysis of Heating Effect

Due to the limitation of the experimental apparatus and the influence of system error, some experimental parameters could not meet the requirements of the scaling criteria. Therefore, individual parameters were adjusted according to the actual situation. Model and experimental parameters are shown in Tables 3 and 4.

Table 3. Parameters of three-dimensional physical model.

Parameter	Model
Oil layer thickness, m	0.2
Porosity, %	40
Oil saturation, %	70
Permeability, mD	10,000
Crude oil viscosity, mPa·s	4759
Initial formation temperature, °C	50
Initial formation pressure, MPa	22.1

Table 4. Parameters of supercritical multi-thermal fluids stimulation.

Parameters	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle	6th Cycle	7th Cycle	8th Cycle
Bottom hole temperature, °C	304.9	327.4	348.7	372.2	390.8	387.5	387.7	390.7
Steam injection rate (cold water equivalent), mL/min	40	40	40	40	40	40	40	40
Gas injection rate, mL/min	20	20	20	20	20	20	20	20
Injection time, min	4	4.5	5	5	5	5	5	5
Soaking time, min	1	1	1	1	1	1	1	1

The variation of temperature at different positions of the model could be obtained through the temperature sensors placed in the model; thus, the variation law of the heating range of CSMTFS could be intuitively analyzed.

2.4.2. Analysis of Production Characteristics

The change of oil production rate and cumulative oil production could be obtained by demulsifying the collected produced liquid, reading the data of oil and water, and calculating the instantaneous production and cumulative production of oil and water. In this way, the production law of CSMTFS could be analyzed intuitively.

2.4.3. Analysis of Heat Loss in Production Process

Reasonable simplification of the three-dimensional model was required to calculate the heat loss of CSMTFS. The calculation process had the following assumptions:

(1) During the experiment, only the heat loss at the top and bottom layers of the model was considered, while the heat loss at the side of the model was not considered. The reason was that the expansion of the heating area during the experiment did not reach the side boundary of the model, and the inner wall of the steel model was coated with thermal insulation material, which had extremely low thermal conductivity.

(2) During the experiment, the oil layer transferred heat to the top and bottom layers by heat conduction, without considering other forms of heat transfer.

(3) During the experiment, the outside temperature of the top and bottom layer was always the initial temperature of the reservoir (50 °C), while the inside temperature was measured by the temperature sensors.

Referring to the calculation method of heat loss in the existing literature [39], the heat flow through the top layer and bottom layer is:

$$\Phi = \frac{\lambda A}{\delta} \Delta T \quad (2)$$

where Φ is the heat flow through the top and bottom layer, J/min; ΔT is the temperature increment, °C; δ is the thickness of the top and bottom layer, cm; A is the heat conducting cross-section area, cm². λ is the thermal conductivity of the top and bottom layer; refer to the existing literature [40] for the thermal conductivity of the top and bottom layer of shale, the value is 2.57 J/(cm·min·°C).

On the plane perpendicular to the wellbore, taking the wellbore as the center, as shown in Figure 5, the heating area was divided into N heating rings with width $dL = 1$ cm. Each heating ring could be considered as an isothermal region, and its temperature was the arithmetic average temperature of the inner and outer boundaries of the heating ring.

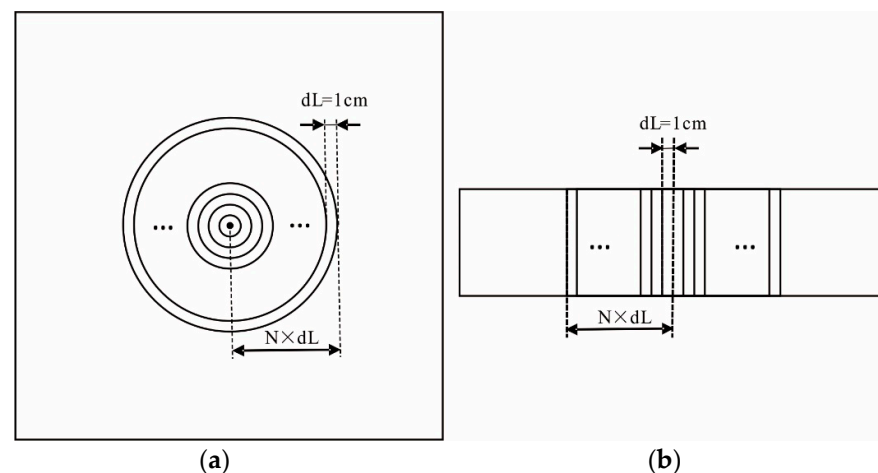


Figure 5. Heating area differential diagram. (a) overlooking; (b) side view.

At the end of injection process in each cycle, the sum of the heat fluxes at the top and bottom layers was equal to the heat loss rate, which can be expressed as:

$$Q_{tl} = \sum_{i=1}^n \Phi_{Ti} + \sum_{i=1}^m \Phi_{Bi} = \sum_{i=1}^n \frac{\lambda_c A_{Ti}}{\delta} \Delta T_{Ti} + \sum_{i=1}^m \frac{\lambda_r A_{Bi}}{\delta} \Delta T_{Bi} \quad (3)$$

The injection rate of heat was equal to the heat carried by the injection of supercritical multi-thermal fluid in unit time, and its expression is:

$$Q_i = i_{sc}(h_{sc} - h_g) \quad (4)$$

where Q_i is the heat injection rate, J/min; i_{sc} is the injection rate of supercritical multi-thermal fluid, g/min; h_{sc} is the enthalpy of supercritical multi-thermal fluid at bottom hole

temperature, J/g; and h_g is the enthalpy of injected thermal fluid at utilization temperature (60°C), J/g.

The ratio of heat loss rate to heat injection rate at a certain time was defined as the percentage of heat loss at that time.

3. Results

3.1. Heating Effect

The temperature distribution at the end of the injection process in each cycle is shown in Figures 6 and 7.

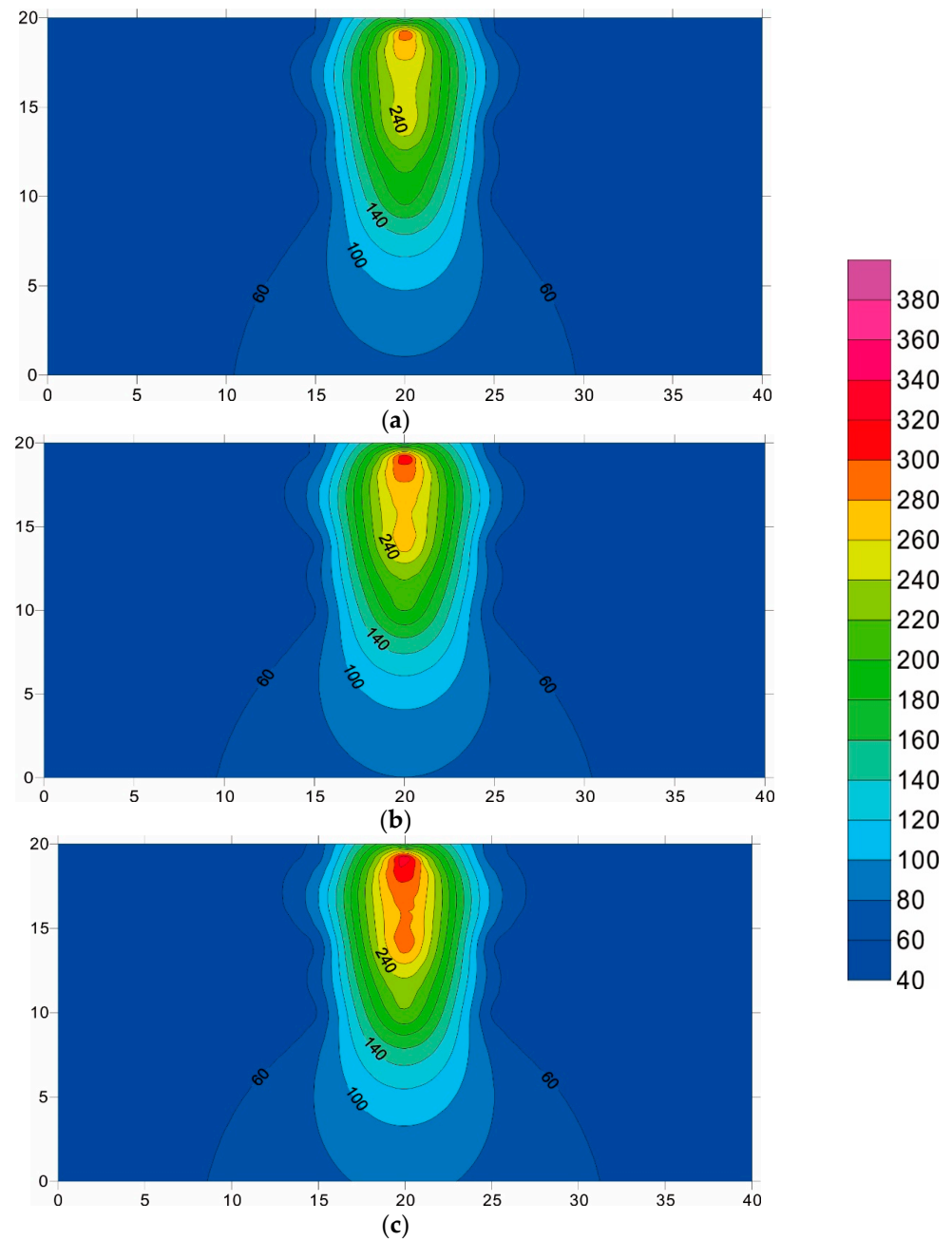


Figure 6. Cont.

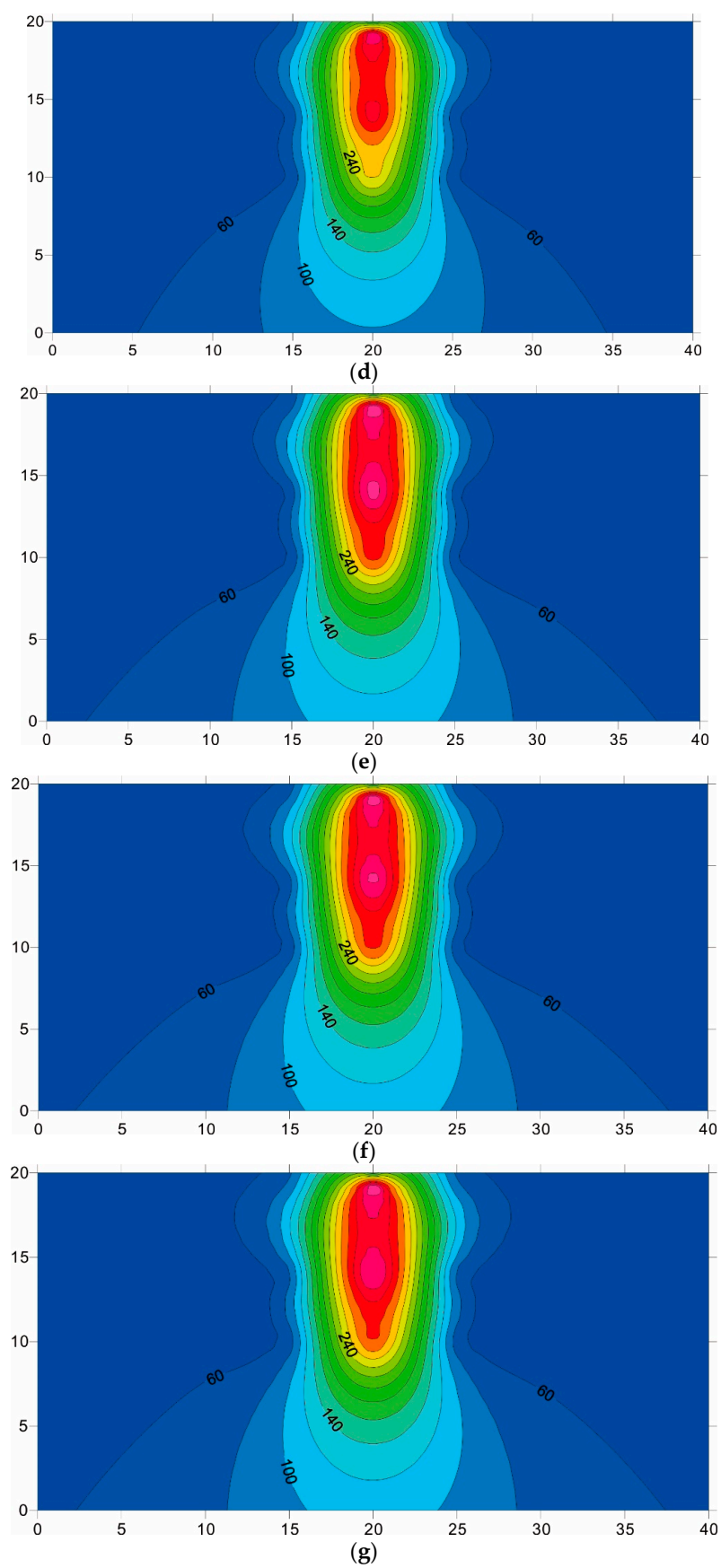


Figure 6. Cont.

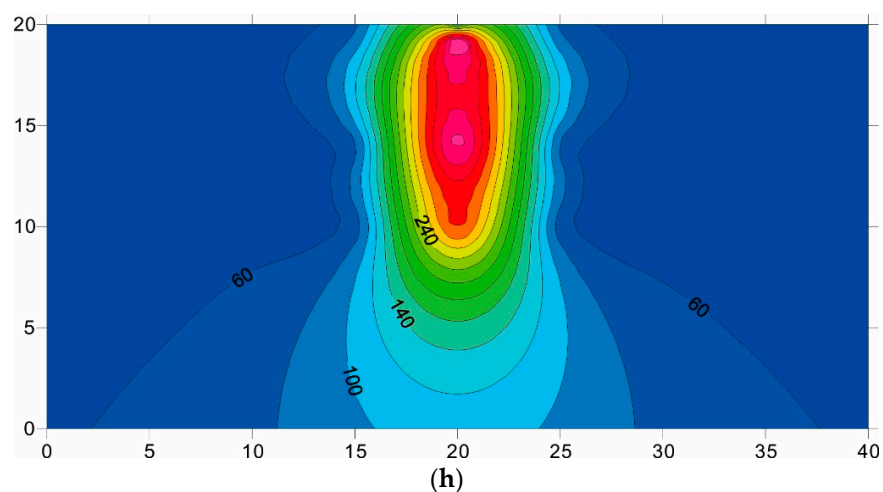


Figure 6. Vertical temperature profile of the oil layer in each cycle. (a) 1st cycle; (b) 2nd cycle; (c) 3rd cycle; (d) 4th cycle; (e) 5th cycle; (f) 6th cycle; (g) 7th cycle; (h) 8th cycle.

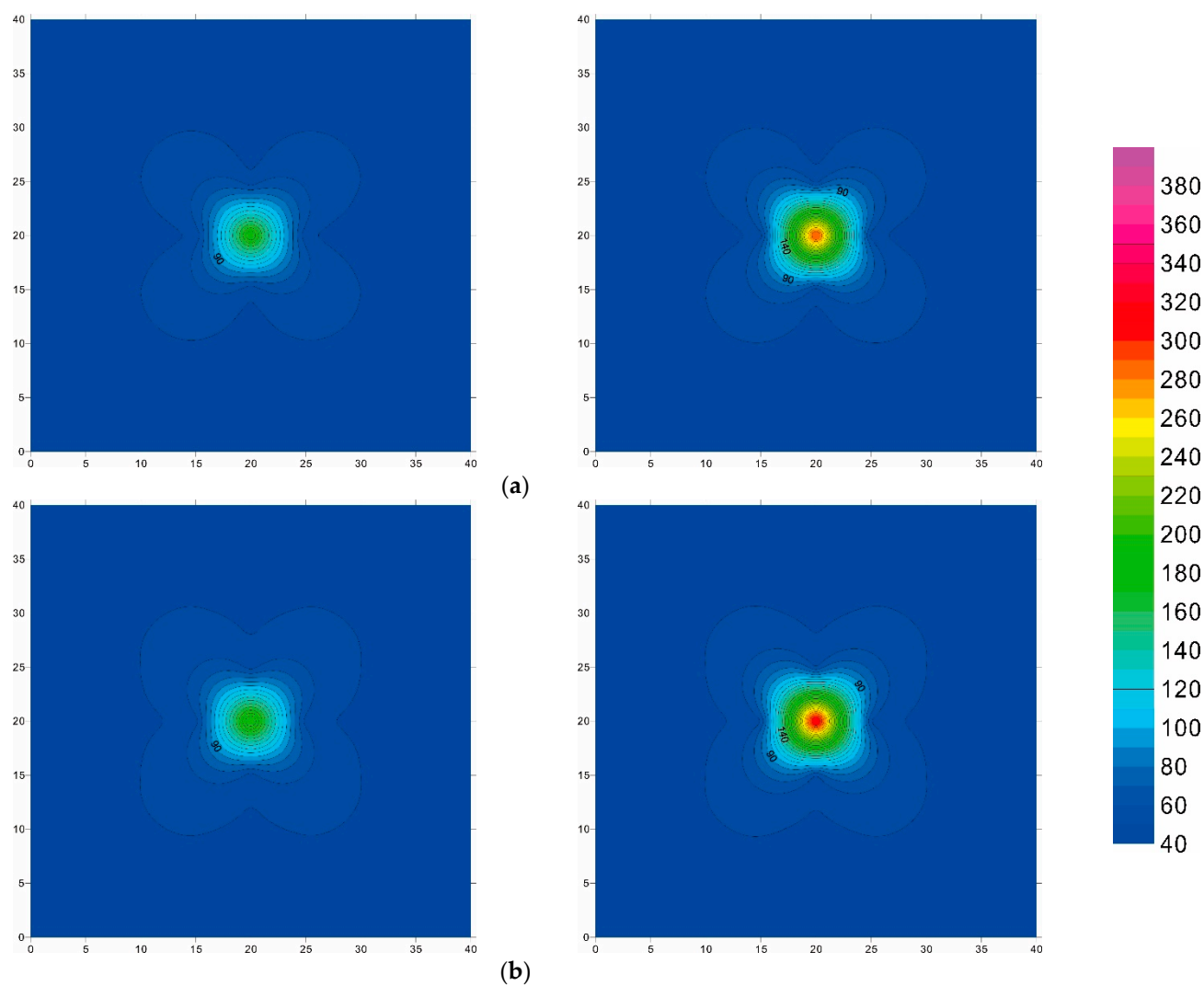


Figure 7. Cont.

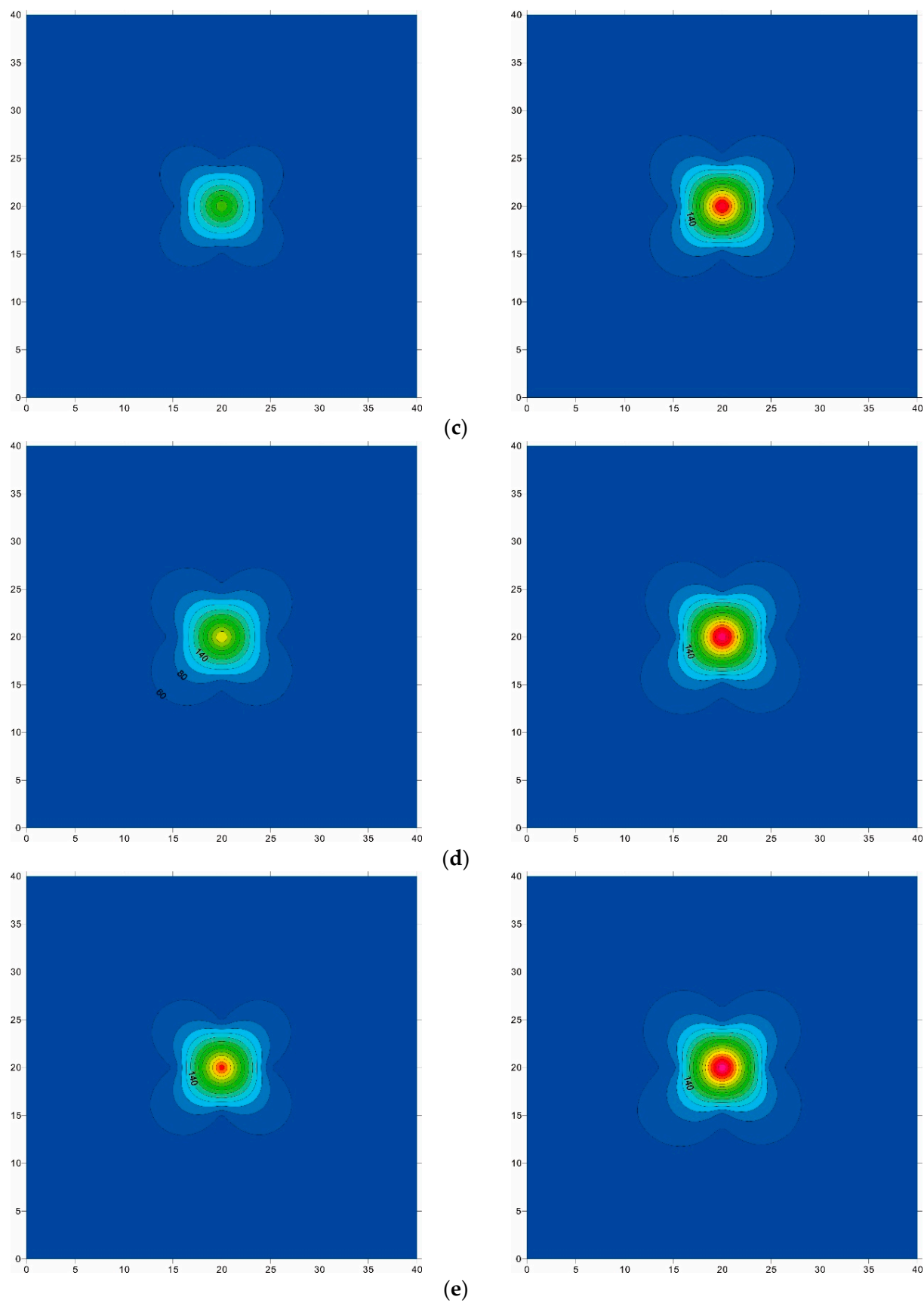


Figure 7. Cont.

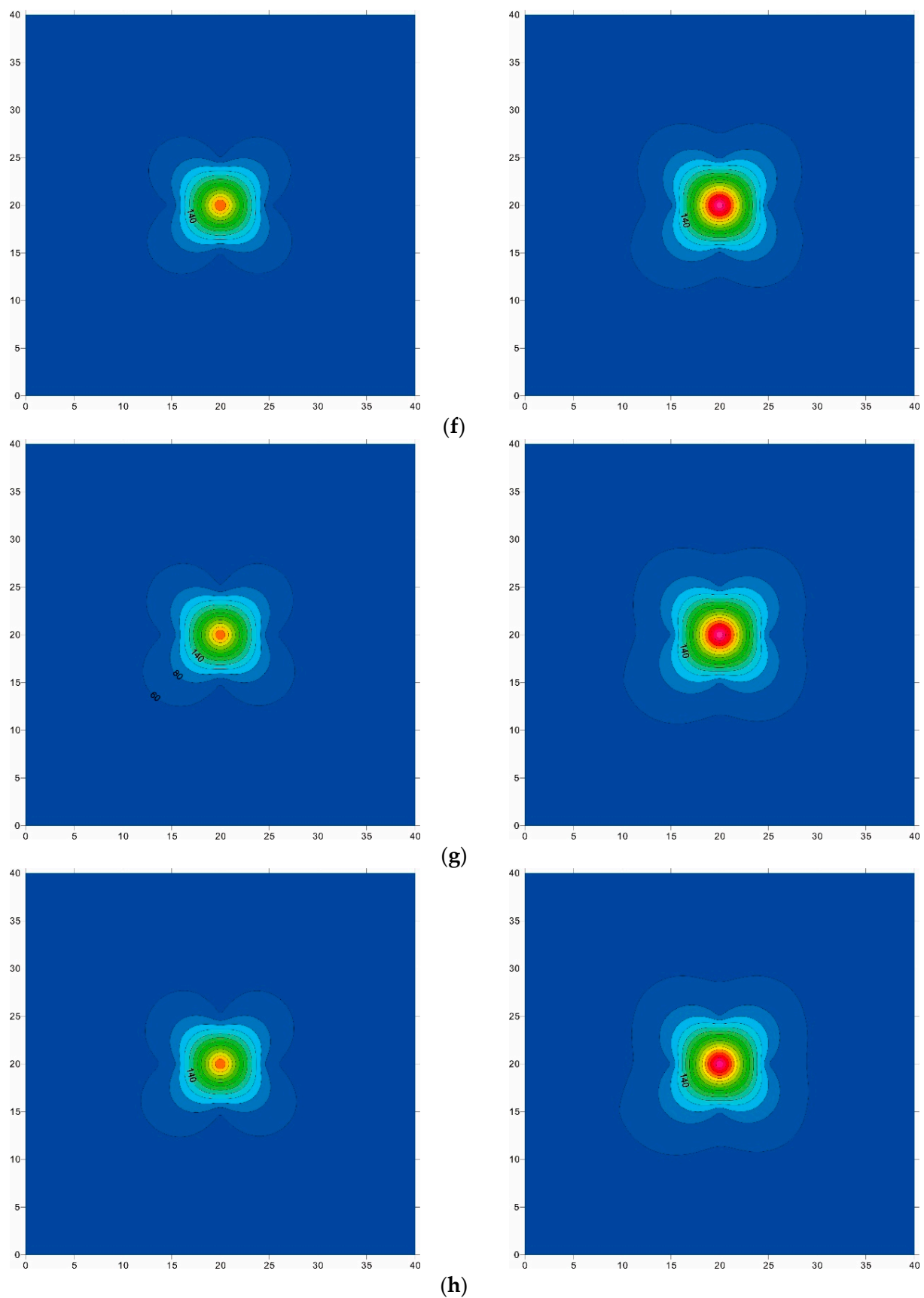


Figure 7. Horizontal temperature profile at the top (right) and middle (left) of the oil layer in each cycle. (a) 1st cycle; (b) 2nd cycle; (c) 3rd cycle; (d) 4th cycle; (e) 5th cycle; (f) 6th cycle; (g) 7th cycle; (h) 8th cycle.

The supercritical multi-thermal fluid is mainly composed of water, nitrogen and carbon dioxide. When the temperature and pressure of a fluid both exceed the critical temperature T_c and the critical pressure P_c , its state is called supercritical state. The critical points of water are $374.15\text{ }^{\circ}\text{C}$, 22.12 MPa , the critical points of nitrogen are $-147.05\text{ }^{\circ}\text{C}$, 3.4 MPa , and the critical points of carbon dioxide are $31.3\text{ }^{\circ}\text{C}$, 7.39 MPa . As a result, as long as the water is in supercritical state, the thermal fluid is the supercritical multi-thermal fluid. Therefore, in the experimental process of this study, the critical temperature and pressure of water was used to determine whether the multi-thermal fluid was in supercritical state.

It can be seen in Figures 8 and 9 that, in the first four cycles, the temperatures at the top and middle of the oil layer were $304.9\text{ }^{\circ}\text{C}$, $327.4\text{ }^{\circ}\text{C}$, $348.7\text{ }^{\circ}\text{C}$ and $372.2\text{ }^{\circ}\text{C}$, respectively. The temperature gradually increased, but the maximum temperature did not exceed $374.15\text{ }^{\circ}\text{C}$, so there was no supercritical multi-thermal fluid area in this stage. The reason was that when the experiment started, the temperature of the oil layer was not high enough. On the other hand, taking $60\text{ }^{\circ}\text{C}$ as the temperature limit of the heating area in the oil layer, the heating area of the model had been effectively expanded in the first four cycles, and the radius of the heating area had increased from about 5 cm in the first cycle to about 7.5 cm in the fourth cycle. When the experiment proceeded to the fifth cycle, the heating area had further extended. More importantly, the temperature of the upper part of the oil layer had reached the maximum temperature of $390.8\text{ }^{\circ}\text{C}$, indicating that a supercritical multi-thermal fluid chamber began to shape in the oil layer at this time.

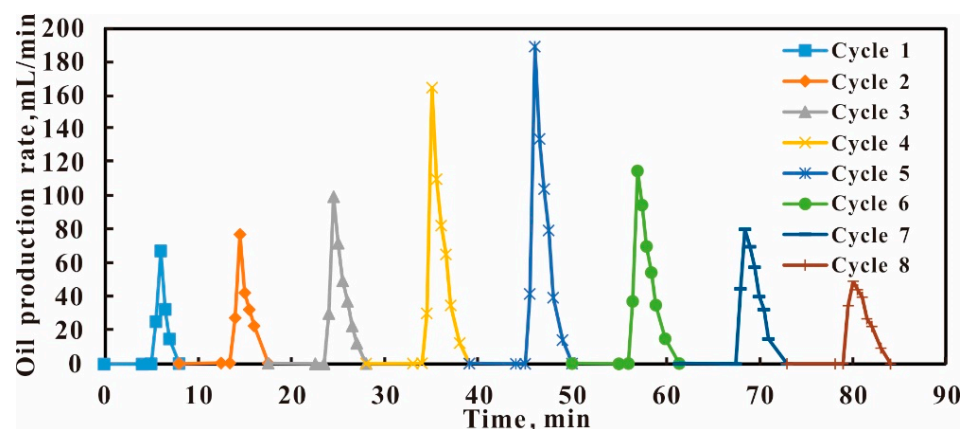


Figure 8. Oil production rate in each cycle.

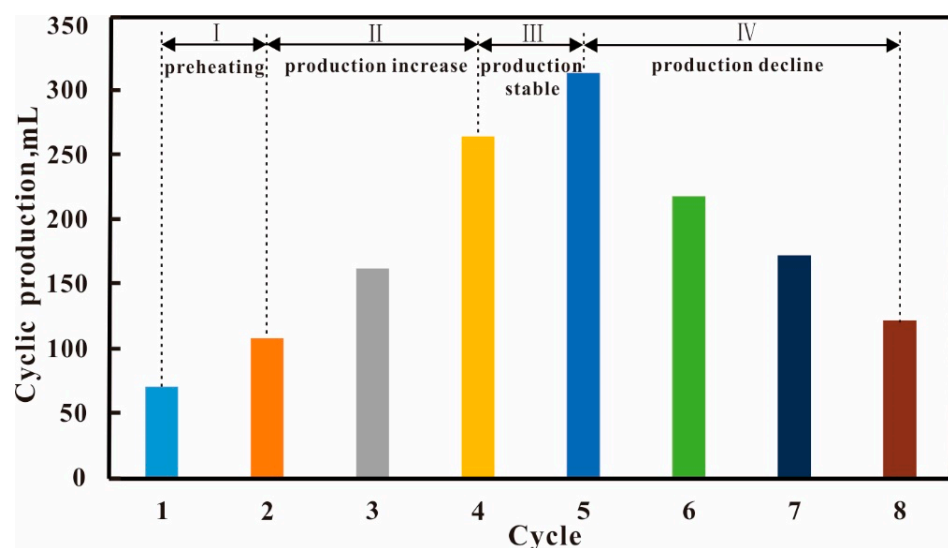


Figure 9. Production distribution in each cycle.

From the sixth to the eighth cycle, the temperature of the upper part of the oil layer was stable at about 390 °C, indicating that the thermal fluid heated the oil layer in supercritical state at first, but after its temperature dropped below the critical temperature, the thermal fluid heated the oil layer in hot water state.

3.2. Production Characteristic

The oil production rate, histogram and cumulative oil production of each cycle in the experiment are shown in Figures 8–10.

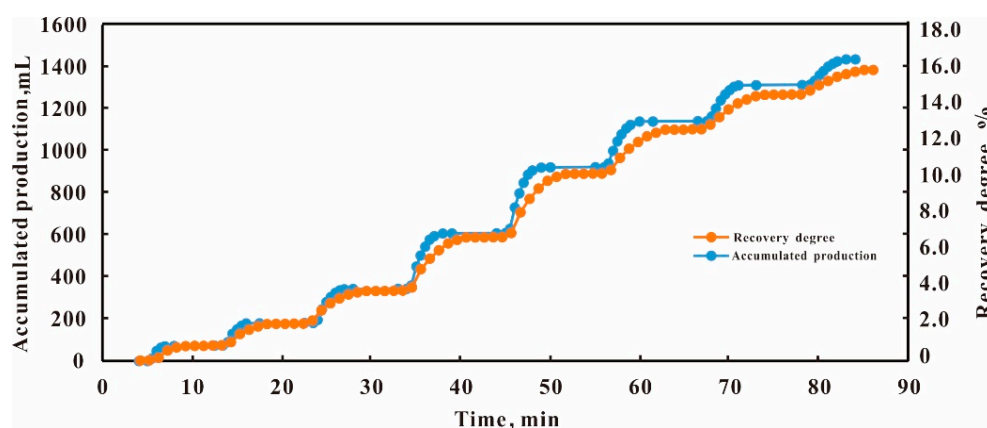


Figure 10. Cumulative oil production and recovery degree of the cyclic stimulation process.

Previous studies have shown that multi-thermal fluid stimulation has a high production and high oil production rate in the early stage, and its production continues to decline and the oil production rate decreases with the increase in stimulation cycles [8,36,41,42]. While in the process of CSMTFS, the production of each cycle increased to the peak first and then decreased gradually. On this basis, the production process was divided into four stages, namely, preheating stage, production increase stage, production stable stage and production decline stage, as shown in Figure 9.

Stage I is the preheating stage (first–second cycle). At this stage, the oil production rate was so low that the cumulative oil production increased slowly, and the increase in oil production rate was not obvious. In this stage, although the temperature of the injected supercritical multi-thermal fluid was very high, the reservoir temperature was equal to the original formation temperature, far lower than the temperature of the supercritical multi-thermal fluid. After the supercritical multi-thermal fluid was injected into the reservoir, it quickly dissipated heat and condensed to non-condensate gas and hot water, which could not effectively heat the reservoir. Moreover, the injection volume in the early stage was relatively small. These factors made the heating effect and diffusion ability of the thermal fluid both relatively poor, which led to a small heated area of the oil layer. The final manifestation was that the oil production rate at this stage was low, the cumulative oil production increased slowly and the oil production rate increased slightly.

Stage II is the production increase stage (second–fourth cycle). At this stage, the oil production rate increased rapidly and the cumulative oil production increased gradually. With the increase in stimulation cycle, the temperature of the oil layer gradually increased, and the supercritical multi-thermal fluid injected into the oil layer did not condense into hot water rapidly. In this process, the supercritical multi-thermal fluid chamber gradually formed, which could heat the oil layer more effectively. In this way, the range of heating area in the oil layer was obviously increased both vertically and horizontally, and the amount of crude oil that could flow was also significantly increased. Therefore, the oil production rate increases rapidly, and the cumulative oil production increases gradually at this stage.

Stage III is the production stable stage (fourth–fifth cycle). At this stage, the oil production rate reaches the peak gradually, and the cumulative oil production increases

rapidly. During this process, the heating area of the supercritical multi-thermal fluid was basically unchanged, the shape of the formed supercritical multi-thermal fluid chamber was generally stable, and the supercritical multi-thermal fluid continuously and stably heated the oil layer. At this time, the oil saturation in the heating area was still at a high level, and the supply capacity of oil was strong. Therefore, the oil production rate was large and increased to the peak gradually, and the cumulative oil production increased rapidly.

Stage IV is the production decline stage (fifth–eighth cycle). At this stage, the oil production rate decreases gradually and the oil production increases slowly. The reason was that the injection temperature, injection rate and periodic injection volume were basically constant at the last stage of the CSMTFS process, while the expanding speed of the heating area gradually slowed down, and the stimulations of the first–eighth cycle made the oil saturation in the heating area of the oil layer gradually decrease to a low level. As a result, the heating area of the oil layer had insufficient oil supply capacity for the well, which led to a significant decline in oil production rate and a gradual slowdown in the increase in cumulative oil production at the later stage of the experiment.

3.3. Heat Loss in Production Process

As mentioned above, the variation of heat loss in each cycle of the CSMTFS process is calculated as shown in Figure 11.

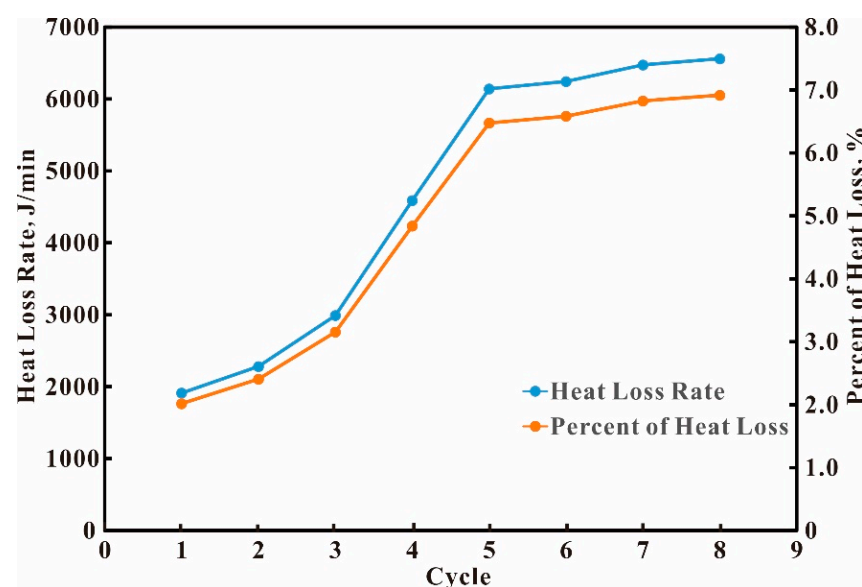


Figure 11. Heat loss rate and percentage in each cycle.

In the preheating stage (first–second cycle), most of the supercritical multi-thermal fluid was rapidly condensed into hot water and the heated area in the oil layer was very small, which led to the area of heat loss on the top and bottom layer being small as well. As a result, heat loss rate and heat loss percentage were at a low level. In the production increase stage (second–fourth cycle), the oil layer was gradually and effectively heated, and the heating range was continuously expanded, so the area of heat loss in the top and bottom layer was gradually increased. Based on this, the heat injection rate, heat loss rate and heat loss percentage increased continuously, and the heat loss percentage increased to the maximum in the fourth cycle. In the production stable stage (fourth–fifth cycle), the heating range and supercritical multi-thermal fluid chamber were expanded to the maximum and remained stable. The area of heat loss in the top and bottom layers also expanded rapidly; thus, the heat injection rate and heat loss rate increased rapidly, which made the percentage of heat loss increase to the maximum in the fourth cycle and then decrease slightly. In the production decline stage (fifth–eighth cycle), the heating range and supercritical multi-thermal fluid chamber remained stable, and the area of heat loss

generated in the top and bottom layer was also stable. Therefore, the heat injection rate was basically stable, while the heat loss rate and percentage of heat loss increased slightly.

Based on the temperature distribution at different production stages in the process of multi-thermal fluid flooding [27], the heat loss at different production stages could be obtained by calculation. The calculation method of heat loss was similar to that of CSMTFS. Based on the parameters in reference [43], the calculated heat injection rate of multi-thermal fluid flooding is 14,380.5 J/min, and the calculation results of heat loss at each production stage are shown in Table 5.

Table 5. Heat loss at different production stages in multi-thermal fluid flooding.

Production Stage	Heat Loss Rate, J/min	Percentage of Heat Loss, %
Rapid effect stage	323.7	2.25
Rapid decline stage	742.3	5.16
Slow decline stage	1343.4	9.34

The calculation results showed that the heat loss rate and percentage of heat loss increased rapidly with the progress of the production stage in the multi-thermal fluid flooding. After the production entered the slow decline stage, the heat loss percentage reached the maximum value of 9.34%, which was higher than the peak value of 7.12% in the process of CSMTFS. The temperature of the supercritical multi-thermal fluid was much higher than that of the thermal fluid in the literature [21], but it can be seen from the results in Table 5 and Figure 11 that the heat loss during the CSMTFS process was smaller, which indicates that CSMTFS can more effectively reduce heat loss.

4. Discussion

During all stimulation cycles, there was always a low temperature zone on the top of the oil layer at the end of the injection process. The reason was that the non-condensable gas (mainly nitrogen) existing in the supercritical multi-thermal fluid accumulated to the upper part of the oil layer under the action of gravity differentiation and formed a thermal insulation layer. Before the stimulation experiment entered the last stage (fifth–eighth cycle), there was no supercritical multi-thermal fluid chamber in the model, which indicated that the oil layer was heated by thermal fluid in a hot water state after the thermal fluid was injected into the model. After the experiment entered the late stage, a small supercritical multi-thermal fluid chamber (about 2 cm in radius) was formed in the upper part of the model after the supercritical multi-thermal fluid was injected into the model. Outside the supercritical multi-thermal fluid chamber, the thermal fluid still existed in the hot water state and flowed downward under the action of gravity to heat the lower part of the model. In the cyclic stimulation process, although the supercritical multi-thermal fluid chamber was relatively small, the heat carrying capacity of the supercritical multi-thermal fluid was much higher than that of multi-thermal fluid, which effectively solved the problem of insufficient heat carrying capacity of multi-thermal fluid stimulation. Previous studies have shown that the injection temperature of conventional multi-thermal fluid stimulation is generally below 300 °C, and the optimized temperature under field conditions is mostly 240 °C; the injection pressure is 10 MPa [9,44,45]. Under this condition, the main heat carrier of the multi-thermal fluid is steam and its enthalpy is only 1038.32 kJ/kg. By contrast, in this experiment, the injection pressure was 22.1 MPa and the minimum injection temperature was 304.9 °C, while the maximum injection temperature was 390.8 °C; the enthalpy of steam under this condition is 1358.68–2640.39 kJ/kg, which is 30.85–154.29% higher than that of conventional multi-thermal fluid.

In the cyclic stimulation process, the production stable stage was the main oil production stage, which accounted for 40.32% of the total oil production. The production decline stage was the subsidiary oil production stage, which accounted for 35.81% of the total oil production. In contrast, the sum of oil production of the preheating stage and production increase stage was lower, accounting for only 23.87% of the total oil production.

The reason was that in the early stage of the experiment, the heating effect on the oil layer was relatively poor and the production was relatively low. Taking into account the effect of cyclic injection volume on production in the process of multi-thermal fluid injection [41,42], in the production process, the cyclic injection volume can be appropriately increased in the early stage of cyclic supercritical multi-thermal fluid stimulation to shorten the time required for the preheating stage and thus improve production.

The production process in a single cycle of cyclic supercritical multi-thermal fluid stimulation was similar to that of multi-thermal fluid stimulation [46], which could be divided into three stages, namely, the drainage stage, production increase stage and production decline stage. The oil production rate increased from a low level to the peak and then decreased gradually. The reason was that after the supercritical multi-thermal fluid was injected into the model, the water saturation and temperature in the area near the wellbore were very high, and there was a drainage period in the early stage of well opening after soaking. After the drainage stage, the temperature of the heated area was still high and its liquid supply capacity was strong, so the oil production rate was large. With the increase in production time, as the heat of the oil layer was lost from the top and bottom layers and carried out by the output liquid, the temperature of the heated area was gradually reduced, and the pressure of the oil layer was also gradually reduced, so the oil production rate began to decline rapidly. In contrast to the high-production and low-production periods in the production experiment of multi-thermal fluid stimulation [8,36], there was no production stable period in the laboratory experiment, because the volume of the model was small and the amount of stored elastic potential energy was small.

This study shows that CSMTFS has the characteristics of high heat carrying capacity and minor heat loss compared with conventional stimulation methods (CMTFS and CSS), so it can efficiently enhance the heating effect of huff and puff operation on the formation and improve thermal efficiency. In addition, the injection of multi-thermal fluids and steam has the problems of high fuel consumption and high water treatment requirements, which leads to high production cost, and this problem is particularly prominent in the recovery of offshore heavy oil reservoirs. The generation of supercritical multi-thermal fluid can directly use oily wastewater, which greatly reduces the cost of fuel and water treatment, and thus improves the economic benefit of the oilfield. At the same time, due to the complex steam generation process of offshore platforms, there are many steam generation and injection pipelines, and pipeline leakage and corrosion problems are prominent. In contrast, the generation process of supercritical multi-thermal fluid is relatively simple, which can significantly reduce the cost of pipeline maintenance. Of course, due to the high temperature and high pressure of supercritical multi-thermal fluid, it puts forward higher requirements for the temperature resistance and pressure resistance of various pipelines, which can be considered as a limitation of this technology. In general, supercritical multi-thermal fluid stimulation meets the demand of “cost reduction and efficiency increase” in the current oil and gas field development process, and can be used as an important alternative technology for offshore heavy oil recovery.

It is worth pointing out that, since the recovery of crude oil is only about 16% through nine cycles of huff and puff in this study compared with conventional heavy oil thermal recovery technology, it may seem that cyclic supercritical multi-thermal fluid stimulation does not show obvious advantages in enhancing heavy oil recovery. However, it should be noted that the oil well in this study only penetrates half of the thickness of the oil layer. If all the oil layers are drilled through and the process parameters are reasonably optimized, the degree of crude oil recovery through cyclic supercritical multi-thermal fluid stimulation will most likely exceed 25%, which is superior to the development effect achieved by other conventional thermal fluid huff and puff. The technique of cyclic supercritical multi-thermal fluid stimulation is the application of supercritical multi-thermal fluid in heavy oil recovery. Although the supercritical multi-thermal fluid was first proposed for the problems of offshore heavy oil recovery, it also can be applied to onshore heavy oil reservoirs, especially for onshore deep heavy oil reservoirs. In conclusion, cyclic supercritical multi-thermal

fluid stimulation can indeed overcome the problems of conventional heavy oil thermal recovery technology in offshore heavy oil development, and is expected to achieve better development results while reducing costs.

5. Conclusions

Through this study on the process of CSMTFS, the following conclusions can be obtained:

(1) The whole development process of CSMTFS can be divided into four stages, namely, the preheating stage, production increase stage, production stable stage and production decline stage. The production stable stage was the main oil production stage, while the production decline stage was the secondary oil production stage. The sum of oil production in these two stages accounted for 76.13% of the total oil production.

(2) The temperature and heating area of the oil layer increased first and then tended to be flat. There was no supercritical multi-thermal fluid chamber in the early and middle stages of the CSMTFS process, and only a small range of supercritical multi-thermal fluid chamber was formed in the last stage of the CSMTFS process. The enthalpy value of supercritical multi-thermal fluid was significantly increased compared with that of multi-thermal fluid, which effectively solved the problem of insufficient heat carrying capacity of multi-thermal fluid.

(3) In the process of cyclic supercritical multi-thermal fluid stimulation, the percentage of heat loss increases first and then tends to be stable; the maximum is 7.12%. Compared with conventional heavy oil thermal recovery technology, the percentage of heat loss in the process of cyclic supercritical multi-thermal fluid stimulation is lower.

Cyclic supercritical multi-thermal fluid stimulation has effectively solved the problems of conventional heavy oil thermal recovery technology in offshore heavy oil recovery, and has significantly improved the development effect, cost, heat carrying capacity, heat loss, etc. It is indeed a new improved-oil-recovery technique for offshore heavy oil.

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