Energy Proceedings
Vol 50, 2025
ISSN 2004-2965

Three-dimensional Physical Simulation of Multi-component Thermal Composite Flooding in Shallow-thin Ultra-heavy Oil Reservoirs

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ABSTRACT

Block C of Sinopec Shengli Oilfield is a typical shallow-thin ultra-heavy oil reservoir. After multiple cycles of steam huff and puff, the reservoir faces issues such as low utilization, low well production, and high water cut. Based on the geological and production parameters of the target block, a three-dimensional physical simulation experiment was designed to transition from steam huff and puff to multi-component thermal composite flooding. The study examined the temperature field and production dynamics characteristics at different stages. The results indicate that during the steam huff and puff stage, the heating range of the reservoir was limited, resulting in a poor development effect, with an oil recovery rate of only 10.4%. In the multi-component thermal composite flooding stage, through the synergistic effect of viscosity reducers, nitrogen, and steam, the final oil recovery reached 57.1%. These findings provide useful insights for the development of shallow-thin ultra-heavy oil reservoirs.

Keywords: The shallow-thin ultra-heavy oil reservoirs, steam huff and puff, multi-component thermal composite flooding, three-dimensional physical simulation.

NONMENCLATURE

Abbreviations	
PV	Pore Volume

1. INTRODUCTION

The world's heavy oil resources are abundant, primarily distributed in countries such as Canada, the United States, Venezuela, and China. The proven reserves are 991.18 billion tonnes, and the recoverable reserves are 126.74 billion tonnes, indicating significant development potential and promising prospects[1]. Unlike conventional heavy oil reservoirs, shallow and thin ultra-heavy oil reservoirs are characterized by being shallow, thin, low in temperature, and highly viscous[2]. The use of conventional steam injection techniques (steam huff and puff, steam flooding) for their development presents issues such as rapid heat dissipation, high thermal loss rate, and low production[3]. Therefore, there is an urgent need for an efficient technology suitable for the development of shallow-thin ultra-heavy oil reservoirs[4,5].

Multi-component thermal composite flooding is a technology that utilizes a combination of chemical agents (viscosity reducers, foams, and oil displacement agents), gases (nitrogen, carbon dioxide, and flue gas), and steam[6]. Through the synergistic effects of these chemical agents, gases, and steam, it expands the heating range and increases the flow radius, thereby enhancing oil recovery[7,8].

The target block for this study is Block C of Sinopec Shengli Oilfield, a typical shallow-thin ultra-heavy oil reservoir. Currently, it is in the late stage of high cycles steam huff and puff, characterized by low reservoir utilization, low well production, and high water cut. Given the shallow burial depth, thin effective thickness, significant thermal loss during steam injection, and high viscosity of the crude oil in this reservoir, the multi-component thermal composite flooding technology combining viscosity reducer, nitrogen, and steam can be considered as a replacement for steam huff and puff. However, the application effect of this technology on Block C is still unclear. Therefore, this study uses heavy oil samples from Block C as experimental samples and conducts three-dimensional physical simulation experiments to analyze the development effect of the multi-component thermal composite flooding.

2. MATERIALS AND METHODS

2.1 Materials and sample preparation

The experimental oil sample used in this paper were taken from Block C of Sinopec Shengli Oilfield, with a viscosity of 57,211 mPa·s at 34°C.The nitrogen gas, with a

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

purity of 99.99%, was provided by Beijing Yongsheng Gas Technology Co., Ltd. The water was prepared according to the ionic composition of the actual formation water, with a salinity of 32,122 mg/L and is of the $CaCl_2$ type. The viscosity reducer was the water-soluble viscosity reducer, which was independently developed by the laboratory and used 0.5wt%. The experimental simulation wells consist of three horizontal wells, all of which were wrapped with a screen mesh to prevent quartz sand from entering the wells and causing wellbore blockage.

2.2 Experimental design

Based on the geological and production parameters of Block C in the Shengli Oilfield and the similarity criteria from previous research, this study converted the reservoir model into a laboratory-scale three-dimensional physical model for investigation[9,10]. The operational parameters for the experimental process were determined in Table 1.

Table 1 Basic parameters between reservoir and 3D model

Parameter	Reservoir	3D Model
Well pattern	horizontal wells	horizontal wells
Well spacing	60m	40cm
Well length	260/6=44m	174/6=30cm
Reservoir thickness	9.1m	6cm
Porosity	35.3%	35%
Initial oil saturation	70%	70%
Permeability	4.6μm^2	5.2μm^2
Oil viscosity (34°C)	57211mPa·s	57211mPa·s
Initial temperature	34°C	34°C
Initial pressure	6MPa	6MPa
Steam temperature	280°C	280°C
Steam quality	0.75	0.75
The first cycle	2880/6=480m^3	854/6=143mL
Cycle increment rate	10%	10%
Soak time	2d	3min
Steam flux	192t/d	20mL/min

2.3 Experimental apparatus and procedures

The apparatus used in the three-dimensional physical simulation experiment for multi-component thermal composite flooding is shown in Figure 1. It mainly includes nitrogen cylinder, gas mass flow controller, ISCO pump, steam generator, heater band, intermediate container, back-pressure valve, pressure gage, hand pump, metering apparatus, temperature and pressure monitoring system.

The specific steps were as follows: (1) Model filling and packaging. The inner cavity of the model is 100cm (length)×30cm(width)×20cm(height), the temperature resistance reaches 300 °C, and the pressure resistance reaches 10MPa.There are two sets of nine-point well patterns on the side of the model, which can be used to arrange horizontal wells. In this experiment, the well pattern consistent with the field is adopted. Three horizontal wells were arranged at the same depth of the oil layer according to the straight line well row. Due to the limitation of the model side well pattern, the distance between well #1 and well #2 was 38 cm, and the distance between well #2 and well #3 was 54 cm. In addition, 7cm thick pottery mud was filled to simulate the impermeable caprock and the bottom layer, and 6cm thick oil sand was filled to simulate the oil layer. There were 85 monitoring points inside the oil layer, which were connected to the sensor. At the same time, a 3mm insulation layer was filled on the wall of the model cavity to prevent the injected fluid from channeling along the wall. A cushion was added above the mud layer, and the upper part of the cushion was the top cover of the steel structure for compaction and sealing of the model.

(2) Check the airtightness of the device. According to Fig.1, the experimental devices were connected, and then nitrogen was injected into the model to check the air tightness of each system.

(3) Model initialization. The model was placed in the constant temperature box. The temperature was set to 34°C (actual reservoir temperature). Crude oil was injected into the model at an injection rate of 2mL/min until the pressure reached the original reservoir pressure and stood for 48 hours. In order to ensure the uniform distribution of reservoir pressure, multiple wells were replaced to inject crude oil.

(4) Carry out experiments. It mainly included two production stages, steam huff and puff stage and multi-component thermal composite flooding stage. In the steam huff and puff stage, three horizontal wells (well #1, well #2, well #3) in accordance with the order from left to right, in turn, single well single cycle steam huff and puff production. When water content reached 98 %, stop production. In the stage of multi-component thermal composite flooding, well #2 was converted into an injection well, followed by injection of 0.2PV viscosity reducer slug, 0.8PV nitrogen slug, and continuous injection of steam at an injection rate of 20mL/min. Well #1 and well #3 were produced. When the water content of the produced fluid reached 98%, the experiment was stopped.

(5) Collect experimental data. Through the data acquisition system, the temperature and pressure changes of each measuring point in the model were

monitored in real time, and the volume of produced liquid and oil was measured in real time.

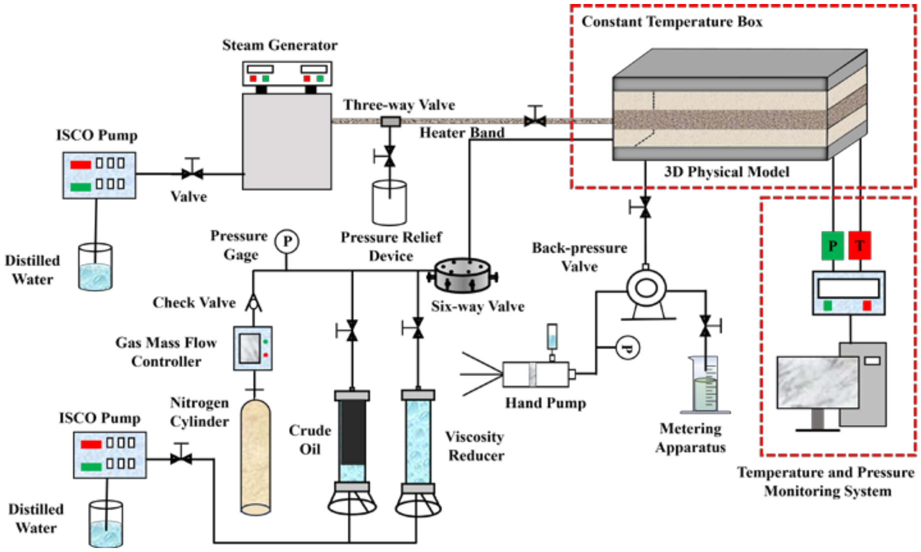


Fig.1 The schematic of the experimental apparatus

3. RESULTS AND DISCUSSION

3.1 Characterization of temperature field distribution

Fig.2 shows the distribution of temperature field at the end of steam injection in different periods of steam huff and puff stage. In this stage, three horizontal wells (well #1, well #2, well #3) in accordance with the order from left to right, in turn, single well single cycle steam huff and puff production. The experimental results showed that the isotherms were mainly densely distributed in the near-well area, and the heating range gradually expanded as the throughput cycle increases. Taking well #2 as an example, the heating radius of steam injection in the first cycle is about 3cm, and the heating radius is about 8cm after three cycles of huff and puff. The temperature around the well increases from 160 °C to 200 °C, but on the whole, most of the reservoir area was still in the area where steam was not affected, indicating that the development effect of steam huff and puff in shallow-thin ultra-heavy oil reservoirs is poor, and the reservoir has not been effectively utilized.

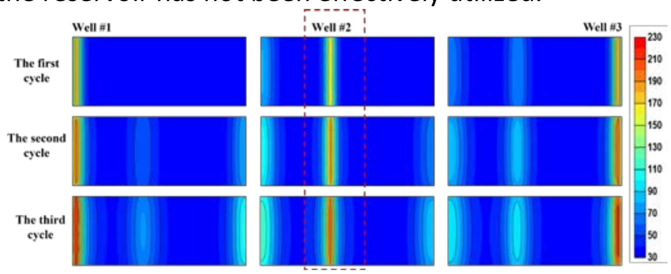


Fig.2 Temperature field after different cycles of steam injection in the steam huff and puff stage

Fig.3 shows the temperature field distribution at different times in the multi-component thermal composite flooding stage. In this stage well #2 was an injection well, which was successively injected with viscosity reducer slug, nitrogen slug and steam. Well #1 and well #3 were production wells. The experimental results showed that after the injection of viscosity reducer slug and nitrogen slug, the temperature around the injection well decreases. This was because the viscosity reducer and nitrogen were injected at room temperature, and the temperature around the well decreases after entering the formation through heat conduction and heat convection. In the early stage of steam injection, the distribution of temperature was relatively concentrated, and it diffused evenly along the wellbore to both sides. With the increase of injection time, due to the large difference in mobility between steam and heavy oil, steam fingering occurred in the process of flooding heavy oil, resulting in uneven temperature distribution. Continuing to inject steam, the affected range was expanded, the steam front reached well #1, and the temperature around the well increased by about 20°C. At 610 minutes, the water cut of the well #1 reached 98%, and the well was shut down. At this time, most of the area on the right side was not affected by steam. At 715 minutes, the steam front reached well #3, and the heating range in the right area increased. At 840 minutes, the water cut of well #3 reached 98%, and the experiment was completed.

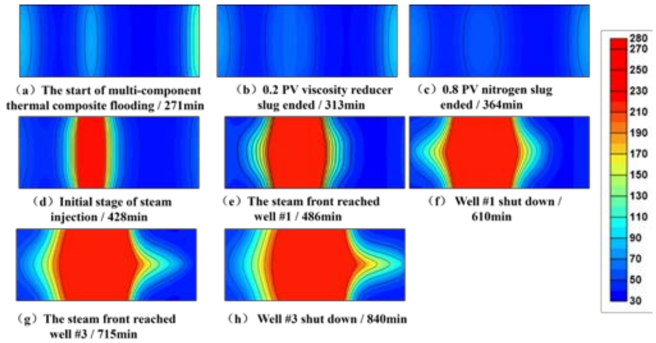
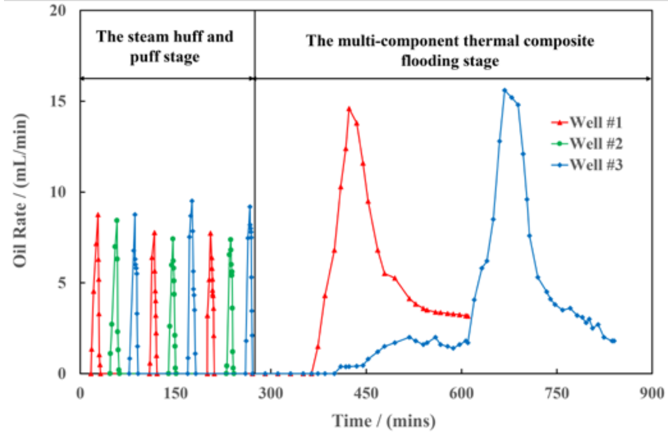


Fig.3 Temperature field at different times in the multi-component thermal composite flooding stage

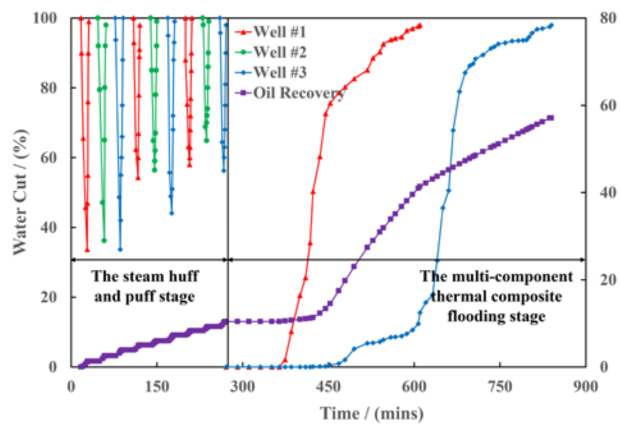
3.2 production dynamic characteristics

The production dynamic curve of three-dimensional physical simulation experiment is shown in Fig.4. It could be divided into two stages: steam huff and puff stage and multi-component thermal composite flooding stage. In the steam huff and puff stage, the oil production rate of the three wells showed a trend of rising first and then falling, and the water cut showed a trend of falling first and then rising. After three cycles of steam huff and puff, the oil recovery was 10.4%. At the same time, the pressure drop corresponding to the three huff and puff cycles measured by the pressure sensor was: 6MPa down to 4.2MPa, 4.2MPa down to 2.8MPa, 2.8MPa down to 1.6MPa, which meet the conditions of turning to flooding.

In the stage of multi-component thermal composite flooding, the viscosity reducer slug was injected in the early stage, and no production was found in the two wells. This was because the crude oil viscosity of the reservoir was high, and the reservoir could not be used only by the emulsification of the viscosity reducer. It also showed that the use of viscosity reducer cold production was less effective in the development of ultra-heavy oil reservoirs. Then the nitrogen slug was injected, and the pressure near the well #2 was measured to increase by 0.8 MPa. This is because the elastic expansion coefficient of nitrogen is high, and it will increase the energy after entering the formation. After steam injection, well #1 was close to well #2, and the production was first seen. With the establishment of thermal connection between wells, the oil production rate of well #1 increases rapidly, and the water cut in the produced fluid was less. Continuous injection of steam, due to the existence of heat connection channel between well #1 and well #2, most of the injected steam entered the left channel, resulting in well #1 water cut began to increase significantly, and well #3 production was low. At 610 minutes, the water cut of the well 1# increased to 98%, and the well was shut down, the oil rate of the well #3 began to rise. At the end of the experiment, the final oil recovery of the multi-thermal composite flooding stage reached 57.1%, which was 46.7% higher than that of the steam huff and puff stage.



(a)Oil rate



(b)Water cut and oil recovery

Fig.4 Production dynamic curve at different stages

4. CONCLUSIONS

In view of the problems of low utilization degree, low oil well production and high water cut after multiple cycles of steam huff and puff in shallow-thin ultra-heavy oil reservoirs, it could be alleviated by turning to multi-component thermal composite flooding. The experimental results showed that the heating range of the reservoir in the steam huff and puff stage was small, mainly concentrated near the well, and the oil recovery was only 10.4%. In the multi-component thermal composite flooding stage, under the synergistic effect of viscosity reducer, nitrogen and steam, the steam had a widespread range, and the oil recovery could reach 57.1%, which was 46.7% higher than that in the steam huff and puff stage, which could efficiently develop shallow-thin ultra-heavy oil reservoirs.

ACKNOWLEDGEMENT

We appreciate the financial support provided by National Natural Science Foundation of China Joint Fund Project (No. U20B6003).

REFERENCE

[1] DONG X, LIU H, CHEN Z, et al. Enhanced oil recovery techniques for heavy oil and oilsands reservoirs after steam injection[J]. Applied Energy, 2019, 239: 1190-1211.

[2] ALPAK F O, KARANIKAS J M. An Optimized-Hybrid In-Situ-Upgrading and Steam-Injection Process for Enhanced-Heavy-Oil Recovery in a Naturally Fractured Reservoir[J]. SPE Journal, 2020, 25(06): 3386-3411.

[3] GU Z, ZHANG C, LU T, et al. Experimental analysis of the stimulation mechanism of CO2-assisted steam flooding in ultra-heavy oil reservoirs and its significance in carbon sequestration[J]. Fuel, 2023, 345: 128188.

[4] WANG Z, WANG Q, JIA C, et al. Thermal evolution of chemical structure and mechanism of oil sands bitumen[J]. Energy, 2022, 244: 123190.

[5] LIN B, SHI C, ZHUANG L, et al. Study on fracture propagation behavior in ultra-heavy oil reservoirs based on true triaxial experiments[J]. Petroleum Exploration and Development, 2020, 47(3): 651-660.

[6] LIU J, DONG T, LIN D, et al. Hydraulic–Thermal–Chemical Coupling Model Considering Hydrate Growth and Aggregation to Study the Hydrate Slurry Multiphase Flow in Oil–Water Systems[J]. Energy & Fuels, 2024, 38(12): 10755-10765.

[7] SUN Q, ZHANG N, LIU W, et al. Insights into enhanced oil recovery by thermochemical fluid flooding for ultra-heavy reservoirs: An experimental study[J]. Fuel, 2023, 331: 125651.

[8] ZHAO S, PU W, JIANG Q, et al. Investigation into the key factors influencing the establishment and propagation of combustion front in ultra-deep high-temperature heavy oil reservoirs[J]. Energy, 2023, 283: 129017.

[9] PANG Z, WANG L, YIN F, et al. Steam chamber expanding processes and bottom water invading characteristics during steam flooding in heavy oil reservoirs[J]. Energy, 2021, 234: 121214.

[10] CHEN Y, YIN H, HE D, et al. Low temperature oxidized coke of the ultra-heavy oil during in-situ combustion process: Structural characterization and evolution elucidation[J]. Fuel, 2022, 313: 122676.