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# Experimental study on the mechanism of enhanced oil recovery by multi-thermal fluid in offshore heavy oil

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ABSTRACT

The multi-thermal fluid process is a new technology that was generated for the development of offshore heavy oil. It has achieved remarkable results in the development of Bohai Oilfield. However, the mechanism of enhanced oil recovery still requires further discussion. Based on the physical similarity criterion, a physical simulation experimental device was independently designed to execute laboratory experiments on different thermal recovery methods (hot water, steam, and multi-thermal fluid), after which the contents of the four components of developed heavy oil were measured and analyzed. The results of the physical simulation experiments indicated that: (1) Thermal viscosity reduction and thermal expansion are the principle mechanisms of hot water flooding; (2) Thermal viscosity reduction and steam distillation are the principle mechanisms of steam flooding, which are accompanied by a certain degree of aquathermal cracking reaction between heavy oil and steam; and (3) thermal viscosity reduction and aquathermal cracking reaction are the principle mechanisms of multi-thermal fluid flooding. Due to the synergistic effect of nitrogen and carbon dioxide, the effect of viscosity reduction by the dissolution effect and gas-water hybrid drive must also be considered. The analysis results of the four components of developed heavy oil by the different thermal recovery methods indicated that the multi-thermal fluid changed the balance of the aromatics-asphaltene-resin regime and strengthened the development degree of the asphaltene component in heavy oil, thereby improving oil recovery through the thermal/physical/chemical mechanism.



## 1. Introduction

Offshore oil and gas fields in China are mainly distributed in Bohai Bay, the East China Sea, the west and east of the South China Sea [1]. The Bohai Oilfield has approximately 2.3 billion tons of heavy oil resources [2]. According to Sheikholeslami et al. [3–5], the significant amount of offshore heavy oil resources has recently attracted much attention and enhanced oil recovery technologies have played an increasingly important role in industry. Enhanced oil recovery (EOR) technologies mainly include the following six aspects: improved water flooding, chemical flooding, heavy oil thermal recovery, gas flooding, microbial enhanced oil recovery, and physical oil recovery, all of which aim to improve the sweep efficiency and/or displacement efficiency [6]. In addition, field tests have proved the effectiveness of thermal technologies in petroleum industry [7–10]. Among those technologies, steam, $CO_2$, $N_2$, flue gas, composite gas, and multi-thermal fluids are widely used as recovery agents. Undoubtedly, the mechanisms of these thermal technologies are vital to the development of offshore heavy oil. As a result, the mechanisms of technologies with steam, $CO_2$, $N_2$, flue gas, and composite gas have been widely examined. Unfortunately, the mechanism of multi-thermal fluid recovery has never been easy due to the presence of nitrogen and carbon dioxide.

As we know, steam is widely used in heavy oil recovery. Willman et al. [11] indicated that thermal expansion of oil, viscosity reduction and steam distillation was the principle mechanisms which were responsible for the additional oil by steam injection. Harding et al. [12] suggested that the presence of nitrogen and carbon dioxide in steam resulted in a slight improvement in the overall recovery and a marked improvement in the rate of oil production. Hong et al. [13] indicated that non-condensable gas injection with steam accelerated oil recovery as a result of the increased volume of displacing gas phase and the lowered oil

*Abbreviations:* Multi-thermal fluid, multiple components thermal fluid; EOR, enhanced oil recovery; SARA, saturates, aromatics, resin, and asphaltene (i.e., the four components); ISCO pump, pump manufactured by the ISCO industries; PV, pore volume; S+A, saturates and aromatics; MMP, minimum miscible pressure; HDNS, horizontal well, viscosity reducer, nitrogen and steam flooding.

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viscosity following the gas dissolution in oil. Nasr et al. [14] indicated that the addition of flue gas to the steam substantially improved both rate and ultimate recovery of bitumen as compared to that obtained by steam alone.

The development of the thermal recovery technique has increased investigations on the feasibility and mechanism of the immiscible $CO_2$ displacement application process. Based on the experimental results of the $CO_2$ displacement process in the West Sak oil field, Hatzignatiou et al. suggested that larger $CO_2$ slug sizes resulted in higher the oil recovery rates [15]. Rojas et al. [16] asserted that immiscible $CO_2$ flooding is an important recovery method, particularly for thin, marginal, or poor heavy oil reservoirs based on scaled model experiments. Malik [17] proved the efficiency and applicability of horizontal injection wells to improve the recovery of the $CO_2$ flooding process. Song et al. [18] developed experimental and numerical techniques to evaluate the performance of $CO_2$ huff-n-puff processes in the Bakken formation, of which either a higher injection pressure or a lower wellhead pressure generated higher recovery during the $CO_2$ huff-n-puff process.

In addition, nitrogen has also been used to improve heavy oil recovery. Wang et al. [19], Liu et al. [20], and Fan et al. [21] concluded that the effect of nitrogen dissolution and separation aided not only in changing the composition of heavy oil but also in improving flow behavior of crude oil. Li et al. [22] and Jia [23] suggested that nitrogen exhibited minimal effect on the viscosity of heavy oil, and the viscosity reduction of heavy oil was highly dependent on the effect of high-temperature steam as exhibited by nitrogen-assisted steam experiments.

Many studies have indicated that flue gas significantly influences oil recovery improvements. Liu et al. [24] indicated that mixing the injection of steam with flue gas strengthens the distillation of steam. Fu et al. [25] concluded that flue gas exhibited significantly improved heavy oil recovery based on a sanding model. Zhu et al. [26] suggested that the effect of flue gas-assisted steam process was much better than the steam injection process based on numerical simulation results. Li et al. [27] indicated that the presence of flue gases significantly improved the heating range and the sweep volume of steam. Ma et al. [28] suggested that flue gas flooding can effectively improve heavy oil recovery according to field tests. Johnson [29] demonstrated the economical applicability of flue gas huff-and-puff method to some shallow reservoirs at current (1989) posted oil prices. Srivastava et al. [30] executed one-dimensional linear coreflood tests with Senlac oil-flue gas and evaluated various operating strategies for heavy oil recovery. Dong et al. [31] performed PVT studies and two-dimensional physical model experiment to examine the effects of the flue gas on viscosity reduction and oil swelling.

Raj et al. [32] compared the effectiveness of $CO_2$, produced gas, and flue gas on the enhancement of Senlac heavy oil recovery, of which the experimental results indicated that the flue gas was the most suitable gas. However, Han [33] and Liu [34] proved the higher recovery suitability of high-temperature composite gas flooding as compared to both steam-$CO_2$ flooding and steam-nitrogen flooding.

However, most of the previous recovery agents are based on conventional steam injection technology. In recent years, a new multi-thermal fluid was introduced into the development of offshore heavy oil reservoirs, such as Shengli Oilfield [35] and Bohai Oilfield [36]. This fluid is a gas mixture of steam and non-condensable gas, and the main components include steam, nitrogen and carbon dioxide. Most of the current research on the application of this multi-thermal fluid in the development process of heavy oil reservoirs focuses on pilot tests and technological process. In 2009, the Shengli Oilfield in China introduced an EOR project. As Ren [37] reported, a multi-thermal fluid stimulation process was performed in a typical multicycle cyclic steam simulation (CSS) well, namely the GDN5-604 well. According to Yu et al. [38], in 2010, a multi-thermal fluid stimulation process was introduced into the Bohai Offshore Oilfield in China to develop an NB35-2S heavy oil block. In terms of the development mechanisms of the multi-thermal fluid in heavy oil reservoir, most of the current research focuses on the conventional gas mixture of steam and non-condensable gas. Stone et al. [39] performed a series of experiments and found that the steam-$CO_2$ injection process exhibited a better recovery performance. Metwally et al. [40] discovered that the co-injection of steam and $CO_2$ tremendously increased oil recovery. Frauenfeld et al. [41] indicated that the co-injection of $CO_2$ with steam was capable of improving oil recovery. Wang et al. [42] observed that the combination effect of all parts of the horizontal well, viscosity reducer, nitrogen and steam flooding (HDNS) significantly increased the steam sweep volume. Ferguson et al. [43] suggested that steam-propane injection at a 5:100 mass ratio of propane:steam accelerated the start and peak of oil production by 20% and 13%, respectively, as compared to steam alone. Monte-Mor and Trevisan [44] found that the co-injection of steam with flue gas accelerated the initiation of oil production as compared to steam. Mohsenzadeh et al. [45] indicated that flue gas injection simultaneously activated the gas dissolution mechanism and high oil/gas density difference mechanism. Therefore, based on the above observations, we focused on the EOR mechanisms of the multi-thermal fluid for the development of offshore heavy oil reservoirs.

In this paper, a series of experiments and research were conducted on the mechanism of enhanced oil recovery by a multi-thermal fluid in offshore heavy oil. The novelty of this paper lies in three aspects: (1) A physical simulation experimental device was independently designed to execute different thermal recovery experiments, especially for the realization of the multi-thermal fluid; (2) The change of four components, specifically the saturates, aromatics, resin, and asphaltene (SARA) content, was introduced to explain the stimulation mechanism of the multi-thermal fluid; and (3) The mechanisms of different thermal recovery methods (hot water, steam, and the multi-thermal fluid) for the offshore heavy oil were analyzed in detail.

## 2. Experiments

### 2.1. Experimental system

To simulate the recovery effect of the different thermal recovery methods (hot water flooding, steam flooding, and multi-thermal fluid flooding) and to examine the EOR mechanism, a physical simulation experiment device was established independently, as presented in Fig. 1. The experimental system mainly includes five parts: a multi-thermal fluid system, a steam system, a hot water system, a constant temperature system, and a data acquisition system. The main experimental devices were employed as follows: a steam generator to provide steam at a certain temperature and at a constant flow rate, a back pressure valve and hand pump to set the needed back pressure, a check valve to prevent gas backflow, an intermediate container to provide the $N_2$-$CO_2$ mixture, a six-way valve to separately provide different kinds of injection agents, an ISCO pump to provide deionized water at a constant flow rate, and a sanding model to simulate the porous media.

### 2.2. Experimental steps

(1) Fabrication of the sanding model: According to the physical properties of the reservoir, 80 mesh glass beads were used to simulate the porous media by pressing the sanding model each time it was filled with 15 g glass beads.