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# Study of Mechanisms of Enhanced Oil Recovery by Multi-Thermal Fluids

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## Abstract

A new process using multi-thermal fluids as an innovative technique for recovery of offshore heavy oil has been used in Bohai oilfield pilot tests. However, the mechanisms of its enhanced oil recovery and reservoir adaptability (sensitivity) have not been studied in depth. Through theoretical, numerical simulation and experimental analyses, the stimulation mechanisms of various components in this process and the coupling effects between these components in terms of enhanced oil recovery are studied and analyzed in detail. In addition, using oil viscosity, rock permeability and heterogeneity parameters of heavy oil reservoirs in the Bohai oilfield, production results and adaptability to reservoir conditions between the standard steam stimulation process and the stimulation process of multi-thermal fluids are compared. The results indicate that the latter process can enlarge the radius of a thermally swept volume, increase formation energy, and reduce heat loss, but the total enthalpy carried by this process drops slightly. Consequently, the process of multi-thermal fluids stimulation is more suitable to heavy oil reservoirs whose oil viscosity is not too high, heterogeneity is relatively weak, oil formation is thin and natural energy is low.

**Key words:** Offshore heavy oil reservoirs; Multi-thermal fluids; Cyclic steam stimulation; Stimulation mechanism; Production efficiency; Reservoir adaptability; Bohai oilfield

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## INTRODUCTION

The Bohai oilfield is rich in heavy oil, and unconventional heavy oil reservoirs whose oil viscosity is larger than 350 mPa·s accounts for a larger portion in this field. However, there has not been any thermal process that is suitable for development and production of offshore heavy oil reservoirs of this type; production rates of offshore heavy oil are very low by using the existing recovery processes such as the standard steam stimulation. We have also applied a technique that used horizontal and multilateral wells and cold production with sand for production of offshore heavy oil reservoirs, but its results were not satisfactory. The main observations were low single well productivity, low production rates and low recovery rates. Moreover, this technique could not reach the desired high production rates and efficiency according to high operating costs and a short service life of an offshore platform. For example, in a south region of Nanbu 35-2 in the Bohai oilfield, its oil viscosity is about 650 mPa·s, the early production rate of a directional well was 10-18 t/d, and the early production rate of a horizontal well was 30-35 t/d. The average recovery rate annually was less than 0.3% and the expected ultimate recovery rate was only 4.2%. For similar other unconventional heavy oil reservoirs in Bohai, their predicted recovery rates are less than 10%. Therefore, we need to develop a new recovery technique that is suitable to the characteristics of offshore heavy oil reservoirs and their development and production.

We use multi-thermal fluids stimulation as a new technique for the development and production of offshore heavy oil reservoirs and study the mechanisms of this new technique in terms of reducing viscosity by heat and dissolution and pressurized drainage. In addition, we analyze its adaptability to reservoir conditions (sensitivity) in order to lay a foundation for the development and production of offshore heavy oil reservoirs.

## 1. A MULTI-THERMAL FLUIDS GENERATOR

Unlike a conventional steam generator, the multi-thermal fluids used in this work are produced by a generator like an aero engine on a well site. The fuel and air burn in the combustion chamber of the generator produces a high temperature gas and water mixture, which form the multi-thermal fluids. $CO_2$ and water can be generated through a diesel oil and air burning reaction; $N_2$ does not participate in the combustion reaction. Therefore, the main components of the multi-thermal fluids are water, steam, $CO_2$ and $N_2$ (see Figure 1).

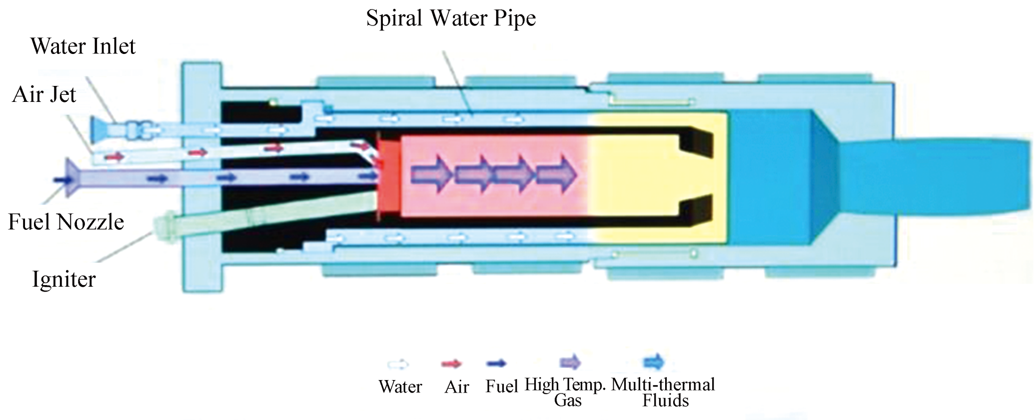



**Figure 1**
**Schematic Diagram for Multi-Thermal Fluids Generation**

## 2. MECHANISMS OF ENHANCED OIL RECOVERY BY MULTI-THERMAL FLUIDS

As mentioned before, diesel and air are combined and combusted at high temperature and high pressure to generate flue gas and a small amount of steam. The latter is mixed with cold water to produce the multi-thermal fluids that are composed of steam, hot water, $N_2$ and $CO_2$. In the Bohai oilfield, such multi-thermal fluids are injected to heavy oil wells to increase well productivity and enhance oil recovery. The thermal recovery equipment needed by these fluids must be small in volume and low in weight to be suitable for offshore platforms. In addition, due to co-injection of $CO_2$ and $N_2$, this new process reduces energy use and is environmentally friendly. Compared to the standard steam stimulation used in onshore oilfields, the composition of the multi-thermal fluids studied is different and their mechanisms are more complex.

### 2.1 Mechanisms of Hot Water and Steam

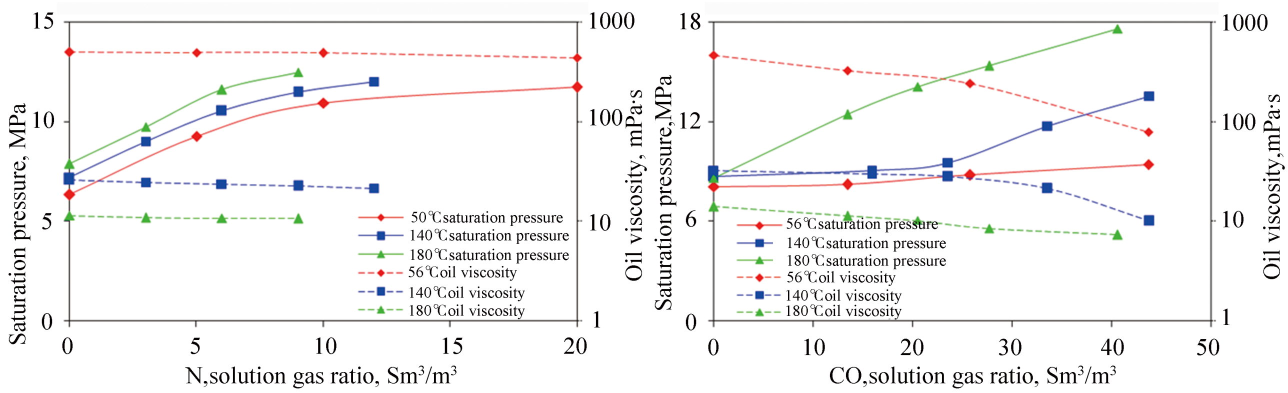
In a process of cyclic stimulation, the heat carried by hot water, steam and other high temperature components in the multi–thermal fluids mainly has five functions: (a) Heating the oil to decrease its viscosity so that its flow resistance is reduced; (b) Heating the formation to increase its elastic energy; (c) Reducing interfacial tension to improve liquid and gas resistance effects; (d) Increasing thermal expansions of fluids and rock to reduce pore volumes and increase well production; (e) Altering the wettability of rock to change the relative permeabilities of oil and water and increase the mobility of oil.

### 2.2 Mechanisms of Gases

The injected gas in the stimulation process of multi-thermal fluids is mainly composed of two parts: the flue gas produced by the combustion of mixed diesel and air and the injected $N_2$ in annuli. The results of previous studies[1-10] showed that while the properties of $N_2$ and $CO_2$ are different, their thermal recovery mechanisms for heavy oil share some common features and also have their respective features. The common features are that both of them can dissolve and expand in oil to reduce the oil viscosity and increase the steam quality. The different features are that $N_2$ can insulate heat, maintain formation pressure, increase well production and reduce residual oil saturation, while $CO_2$ can reduce interfacial tension and have an acidizing effect.

Although both $N_2$ and $CO_2$ can dissolve in oil, their solubility and viscosity reduction scales are different. As we can see from the solubility and corresponding viscosity curves of $N_2$ and $CO_2$ at different temperatures (Figure 2), the solubility difference between $N_2$ and $CO_2$ is quite big. For a reservoir with a depth of 1,000m, formation temperature at 56℃ and formation pressure at 10 MPa, the solution gas-oil ratio of $N_2$ is about 5 $Sm^3/m^3$ (Figure 2a), while the solution gas-oil ratio of $CO_2$ reaches 35 $Sm^3/m^3$ (Figure 2b). When $N_2$ is dissolved in oil, the oil viscosity is decreased from 463.9 mPa·s to 490.6 mPa·s, with a reduction rate of 0.85%. In contrast, the corresponding viscosity is decreased from 436.9 mPa·s to 150 mPa·s when $CO_2$ is dissolved in oil, with a reduction rate of 67.7%, which shows that $CO_2$ is much more effective than $N_2$ in viscosity reduction.

As temperature rises, the dissolving capability of $N_2$ and $CO_2$ in oil is decreasing, and in the process of temperature rising, the contribution rate of dissolved gas to the oil viscosity reduction is getting lower. For $CO_2$, for example (Figure 2b), when temperature rises from 56℃ to 180℃, the viscosity of oil decreases from 463.9 mPa·s to 14.1 mPa·s. At this point, when $CO_2$ is dissolved, the maximum dissolution capacity of $CO_2$ is only 40 Sm$^3$/m$^3$, even if pressure is increased to 18 MPa; the corresponding oil viscosity is merely decreased from 14.1 mPa·s to 7.3 mPa·s. During the whole process, the contribution percent of temperature to viscosity reduction is 98.5%, while the contribution percent of $CO_2$ to viscosity reduction is merely 1.5%.




(a) $N_2$ (b) $CO_2$

**Figure 2**
**Relationships Between GOR and Saturation Pressure and Oil Viscosity With $N_2$ and $CO_2$ at Different Temperatures**

According to the experimental results on $CO_2$, $N_2$ and flue gas for enhancing heavy oil recovery efficiency conducted by Strivastava[11-12], the displacement effects of flue gas are closer to those of $N_2$. Its displacement mechanisms mainly contain two parts: The mechanism of free $N_2$ and the dissolving mechanism of $CO_2$. Furthermore, these two mechanisms compete with each other.

### 2.3 Coupling Effects of Hot Water, Steam and Gas

Through establishing a numerical reservoir simulation model, we can compare the viscosity and pressure distribution of the reservoir oil after injection of steam and multi-thermal fluids, respectively. The results indicate that after injecting steam, the viscosity of the oil drops a lot; after injecting the multi-thermal fluids, although the viscosity reduction is not as great as that after the steam injection, the gas in the multi-thermal fluids produces a larger region of viscosity reduction for the oil around each injection well so that it increases the drainage radius. Furthermore, with injection of steam and the gas from the multi-thermal fluids which heat and are dissolved into the oil, the formation pressure and swept volume become obviously larger, which enhances productivity of each well.

## 3. ADAPTABILITY OF MULTI-THERMAL FLUID STIMULATION TO RESERVOIRS

Compared with the multi-thermal fluid stimulation, the mechanism of the standard steam stimulation is relatively simple. It mainly deals with viscosity reduction by heating, a wettability change of rock and a permeability improvement of oil. In order to compare the production efficiency and reservoir adaptability conditions of these two thermal recovery processes, based on the characteristics of Bohai heavy oil reservoirs, we examine five parameters: reservoir oil viscosity, reservoir thickness, permeability, original oil saturation and the ratio of vertical to horizontal permeabilities. We set up a numerical simulation model to compare the production efficiency of multi-thermal fluid stimulation and steam stimulation under different conditions.

### 3.1 Simulation Model

The CMG thermal software STARS is used in the simulation study. The number of grid blocks in the horizontal plane is 4,800, where the numbers of the grids in the *x*- and *y*-directions are 80 and 60, respectively, with an equal grid size of 10 m. The number of vertical layers is 10, with a grid size of 1 m。In this study, we focus on a horizontal well with a length of 500 m. The time step size is implicitly adapted by STARS, typically with a few days.

The basic parameters of the reservoir model are: The reservoir oil viscosity is 600 mPa·s, the reservoir thickness is 10 m, the horizontal permeability is $2{,}500\times10^{-3}$ μm$^2$, the original oil saturation is 0.73, the ratio of the vertical to horizontal permeabilities is 0.1, the porosity is 35%, the reservoir temperature is 45$^o$C, the reservoir depth is 900 m, the formation pressure is 8.9 MPa, the reservoir saturation pressure is 4.5 MPa, the reservoir oil density is 0.96 g/cm$^3$, the reservoir oil formation volume factor is 1.052 m$^3$/m$^3$, and the solution gas ratio is 3 m$^3$/m$^3$.

### 3.2 Effects of Reservoir Oil Viscosity on Production

Comparing the production efficiency of these two processes with different reservoir oil viscosities (Figure 3), we find out that when viscosity is low, the production efficiency of the multi-thermal fluid stimulation is better than that of the steam stimulation. However, as the reservoir oil viscosity increases, both the cumulative oil production and the production rates of these two recovery processes decrease gradually, and the declining rate of both the production rate and the cumulative oil production of the multi-thermal fluids is much higher than that of the steam stimulation. When the oil viscosity is 1,300 mPa·s, the cumulative oil production and the production rate of these two processes are the same. When the reservoir oil viscosity is lower than 1,300 mPa·s, the efficiency of the multi-thermal fluids is better than that of the steam stimulation. When the reservoir oil viscosity is higher than 1,300 mPa·s, the results are opposite.

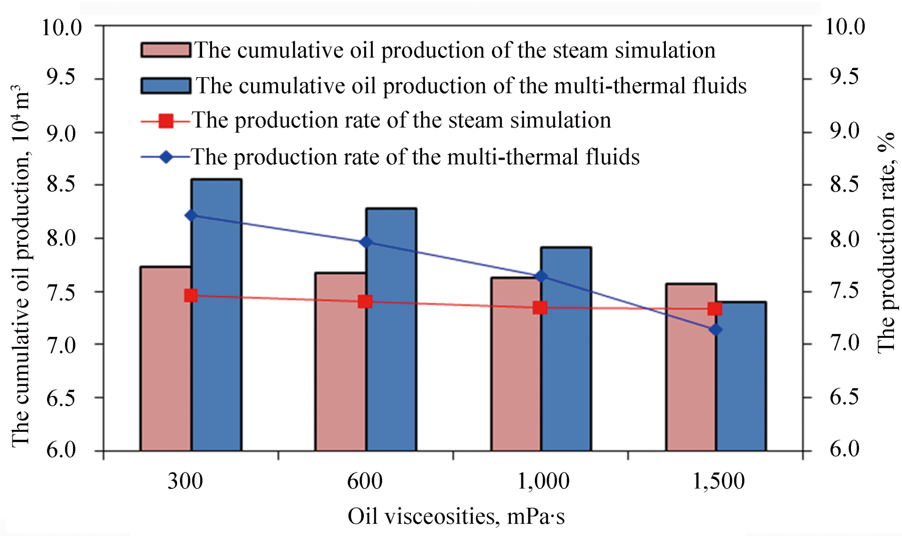
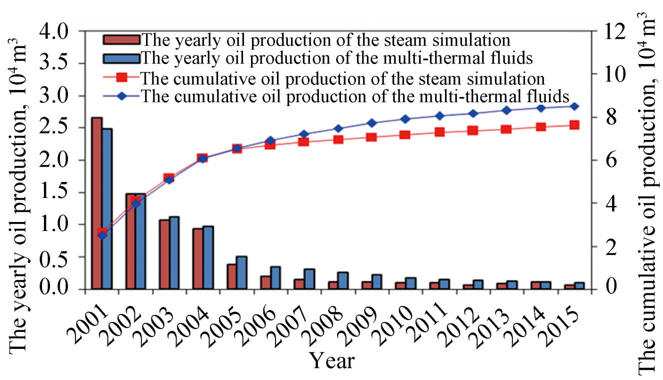
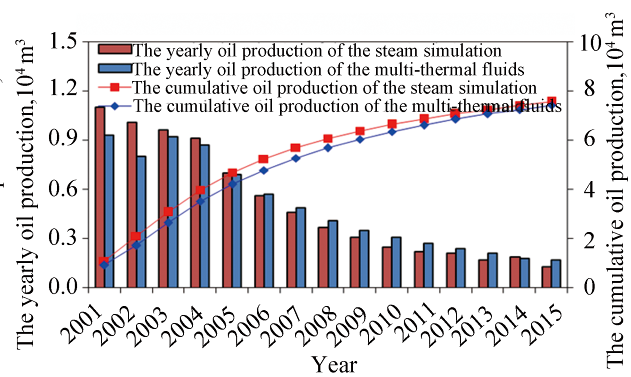



**Figure 3**
**Production Efficiency Comparison of Multi-Thermal Fluid Stimulation and Steam Stimulation With Different Reservoir Oil Viscosities**

It can be seen from the comparison of the yearly oil production and cumulative oil production of the two thermal recovery processes with the oil viscosity of 400 mPa·s and 1,500 mPa·s, respectively (Figure 4) that because the stimulation production technique is of depletion type, at the beginning of production, the formation energy is abundant and viscosity reduction by heating plays a dominant role. The higher the oil viscosity is, the more obvious the viscosity reducing effect by heating is. Hence, at the beginning of production, the annual production of the steam stimulation is higher than that of the multi-thermal fluid stimulation. In the later stimulation stage, since the formation energy is not sufficient, the multi-thermal fluid injection improves the reservoir pressure and its annual production is higher than that of the steam stimulation.




(a) Reservoir Oil Viscosity at 400 mPa·s




(b) Reservoir Oil Viscosity at 1,500 mPa·s

**Figure 4**
**Annual Oil Production and Cumulative Oil Production of the Multi-Thermal Fluid Stimulation and Steam Stimulation Under Different Reservoir Oil Viscosities**

### 3.3 Effects of Reservoir Thickness on Production

It can be seen from Figure 5 that when the reservoir oil viscosity is 600 mPa·s and the reservoir thickness is 5, 10, 15, and 20 m, respectively, the production efficiency of the multi-thermal fluid stimulation at different reservoir thicknesses is always better than that of the steam stimulation. The thinner the oil reservoir is, the more obviously the production increases. This is mainly due to the thermal insulation of the gas in the multi-thermal fluids, which prevents heat loss to overburden and underburden.

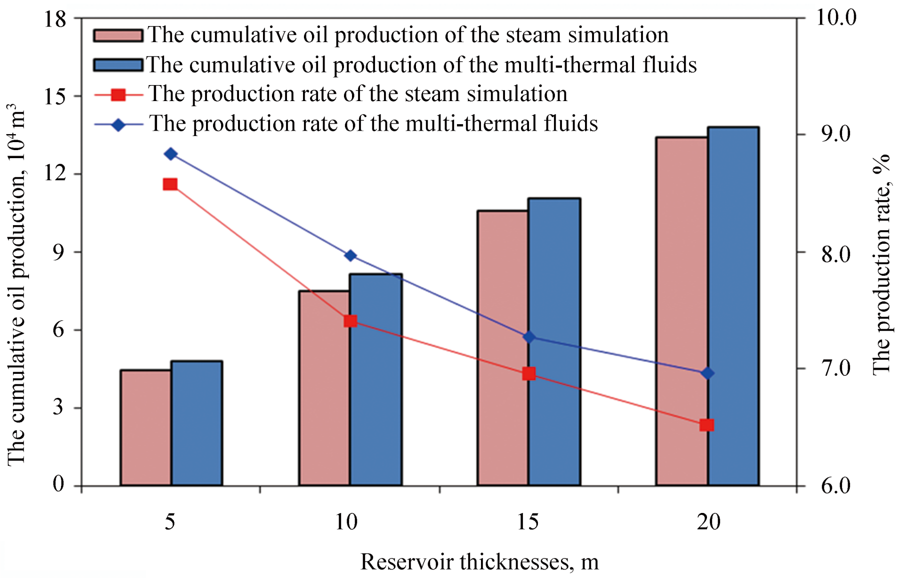
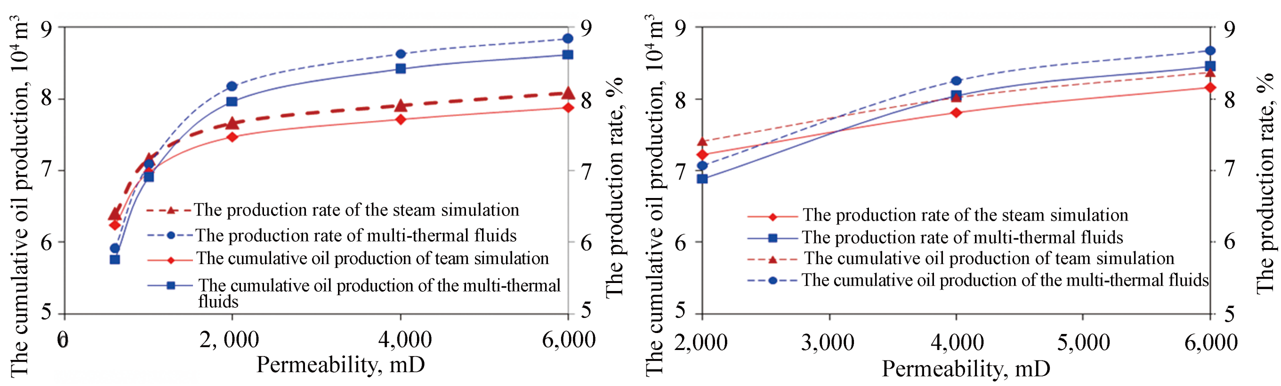



**Figure 5**
**Production Efficiency Comparison of Multi-Thermal Fluid Stimulation and Steam Stimulation for Different Reservoir Thicknesses**

### 3.4 Effects of Permeability on Production

When the viscosity of oil is low, at 400 mPa·s, for example, it can be seen from the comparison of the multi-thermal fluid stimulation and the steam stimulation at different permeabilities (Figure 6a) that as the permeability increases, the increase of the production rates and cumulative oil production of these two processes gradually slows down. When the permeability is less than $1,000 \times 10^{-3} \mu m^2$, the production rate and cumulative oil production of the steam stimulation are higher than those of the multi-thermal fluid stimulation. When the permeability is higher than $1,000 \times 10^{-3}$ $\mu m^2$, the results are opposite. The main reason is that the higher the permeability is, the more serious the steam overlapping phenomenon is. Because of the multiple components of the multi-thermal fluids, this process can heat both the upper and lower formation.

When the oil viscosity is high and increases to 1,500 mPa·s and the permeability is $3,000 \times 10^{-3} \mu m^2$, the cumulative oil production curves of the two recovery processes intersect. At this time, their production efficiency is the same. Compared with the condition where the reservoir oil viscosity is 400 mPa·s, we can see that as the reservoir oil viscosity increases, the upward flowing resistance of heat becomes larger so that it reduces the steam overlapping effect. Therefore, the steam stimulation is more suitable for heavy oil reservoirs with a larger oil viscosity.




(a) Reservoir Oil Viscosity at 400 mPa·s (b) Reservoir Oil Viscosity at 1,500 mPa·s

**Figure 6**
**Production Efficiency Comparison of Multi-Thermal Fluid Stimulation and Steam Stimulation Under Different Permeabilities**

### 3.5 Effects of Original Oil Saturation on Production

From the production efficiency of the multi-thermal fluid stimulation and the steam stimulation under different original oil saturations, it can be seen (Figure 7) that as the original oil saturation increases, the cumulative oil production of both processes increases. However, since higher original oil saturation leads to higher geological reserves, the production rate becomes lower. Compared with the multi-thermal fluid stimulation, the production efficiency of the steam stimulation decreases more. Therefore, the steam stimulation is more sensitive to the change of original oil saturation.

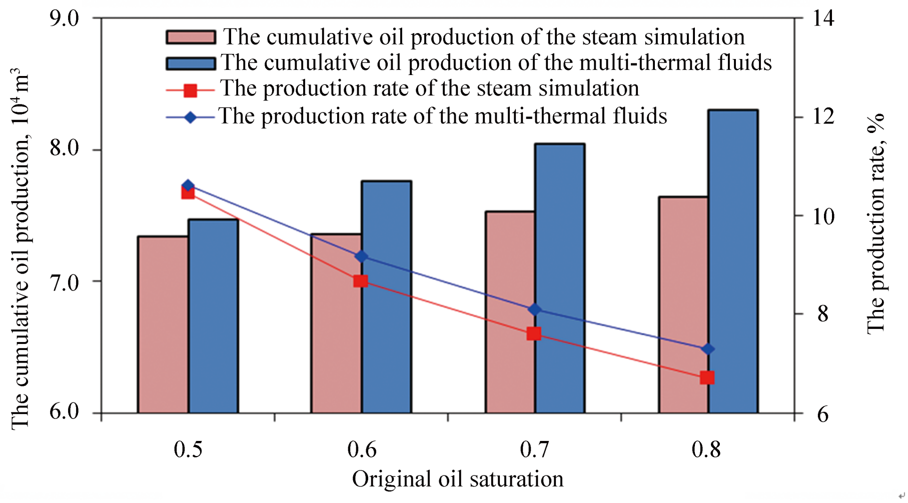



**Figure 7**
**Production Efficiency Comparison of Multi-Thermal Fluid Stimulation and Steam Stimulation at Different Original Oil Saturations**

### 3.6 Effects of Vertical and Horizontal Permeability on Production

When the vertical and horizontal permeability ratio is 0.1, 0.3, 0.5, and 1.0 respectively, it has little effect on the cumulative oil production of the two recovery processes. As the ratio increases, the steam overlapping phenomenon becomes more serious; the cumulative oil production of the steam stimulation first increases and then decreases. In contrast, the cumulative oil production of the multi-thermal fluids keeps increasing and its production efficiency becomes better and better. The difference between these two recovery processes becomes greater. The main reason is that the gas components of the multi-thermal fluids heat up the upper oil layer and the hot water heats up the lower oil layer, which makes the reservoir produce more uniformly in the vertical direction. Meanwhile, the thermal insulation of gas makes the production efficiency of the multi-thermal fluid stimulation increase more rapidly than that of the steam stimulation.

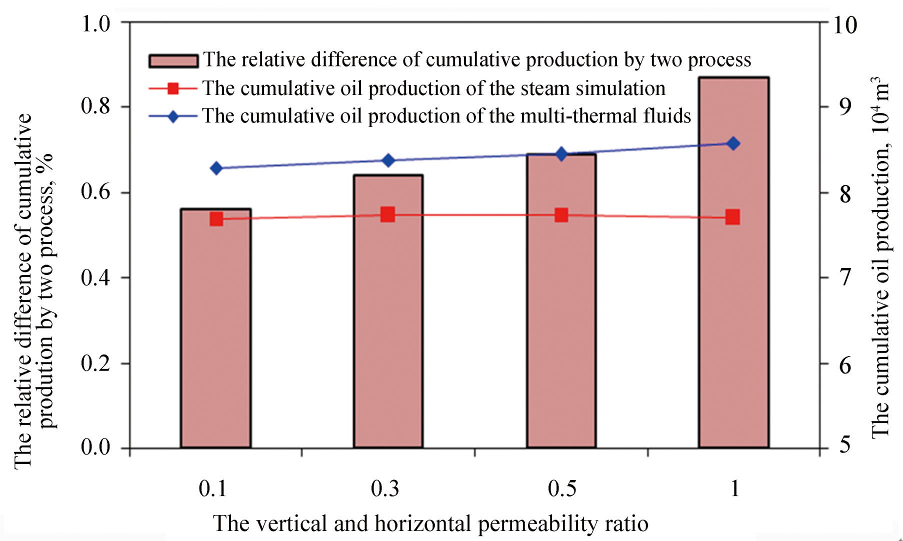



**Figure 8**
**Production Efficiency Comparison of Multi-Thermal Fluid and Steam Stimulation at Different Vertical and Horizontal Permeabilities**

## 4. FIELD APPLICATION OF MULTI-THERMAL FLUID STIMULATION

Based on the study in this work, the reservoir NB35-2 in a southern region of Bohai is chosen to perform a pilot test for the process of multi-thermal fluid stimulation for offshore heavy oil. The NB35-2 reservoir is a heavy oil reservoir, is semi-anticlined, and was originated from the lower section of the Minghuazhen formation; it is a fluvial reservoir and has the characteristics of high porosity, high permeability and high heterogeneity; its oil density and viscosity are large, and its wax and sulfur components are low; the properties are listed in Table 1. NB35-2 started to produce in 2005, in its early stage it produced by cold production from natural energy, and there were 23 production wells, 16 of which were horizontal. An early average production rate was 35t/d per well. Up to October 2010, the average well production rate was 11 t/d, and the reservoir had a daily production rate of 240 t/d and a water cut of 72%.

**Table 1**
**The Reservoir Parameters of NB35-2**

| Depth, m | Oil Viscosity, mPa·s | Oil Density, g/cm$^3$ | Net thickness, m | Permeability, μm$^2$ | Porosity, % | Clay content, % |
|---|---|---|---|---|---|---|
| 900-1,100 | 450-960 | 0.96-0.97 | 6-8 | 2-3 | 30-38 | 3-9 |

In 2010-2014, all the wells were switched to the multi-thermal fluid stimulation and 11 horizontal wells were added with a length of 200-300 m. The injection parameters in the first cycle for each well were: The injceted fluid temperature is 240℃, the multi-thermal fluids consist of 3,500 t hot water, 1,232 t $N_2$, and 264 t $CO_2$, the soak time was 2-3 days, the peak daily production rate per well was 80-134 t/d, the average daily production rate in the first cycle was 60 t/d, the average production rate in this cycle by the multi-thermal fluid stimulation was 1.6 times that by cold production, the first cycle lasted 300 days, and the cumulative production in this cycle was 18,000 t (Table 2). In the southern part of NB35-2, the production increased from 200 t/d to 600 t/d, and its production increased three times (Figure 9).

**Table 2**
**Statistics of Typical Wells in NB35-2**

| Well No. | Cold production | Average production rate by multi-thermal fluid | Production increase times | Days of the first cycle | Cumulative production in the first cycle |
|---|---|---|---|---|---|
| | t/d | t/d | | days | $10^4$ t |
| B33H | 42 | 63 | 1.5 | 290 | 1.8 |
| B34H | 39 | 70 | 1.8 | 325 | 2.3 |
| B36M | 32 | 58 | 1.8 | 330 | 1.9 |
| B43H | 36 | 50 | 1.4 | 224 | 1.1 |
| B44H | 33 | 53 | 1.6 | 310 | 1.6 |
| Average | 37 | 60 | 1.6 | 296 | 1.8 |

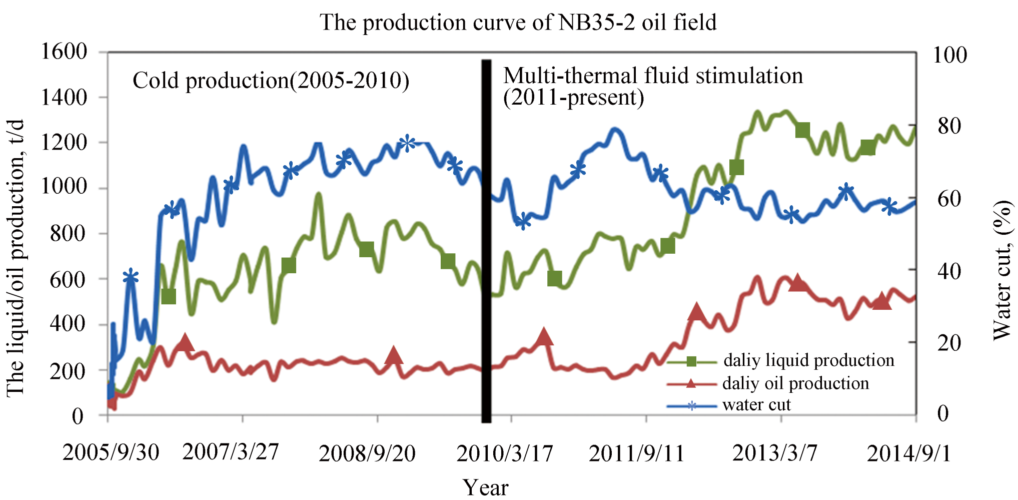



**Figure 9**
**Production Indecies Before and After the Multi-Thermal Fluid Stimulation in the Southern Part of NB35-2**

## CONCLUSION

The mechanisms of the multi-thermal fluid stimulation process are very complicated: The heat carried by hot water has the effects of increasing temperature and reducing viscosity, $N_2$ has the effects of thermal insulation and pressurization, and $CO_2$ has the effects of dissolution and viscosity reduction. The effect of viscosity reduction by gas dissolution is much weaker than that by heat. In addition, the multi-gas combination is rather mutually competitive than collaborative.

At the early stage of the multi-thermal fluid stimulation process, the stimulation plays the role of heating and decreasing viscosity. In the middle and later stages, it plays an increasing role in pressurizing and accelerating drainage. This recovery process is suitable for heavy oil reservoirs whose oil viscosity is lower (less than 1,000 mPa·s), oil formation is thin (less than 10 m), heterogeneity is weak, and natural energy is low.

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