SAGP Experiment of Thin Super Heavy Oil Reservoirs

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Abstract - The objective of the experiments is to investigate oil displacement efficiency and mechanism of super heavy oil reservoir with thin layer and inter layer using non-condensate gas SAGP. Based on the Butler research group proportion model, a two-dimensional physical model of Steam Assisted Gravity Drainage (SAGD) in thin super heavy oil with inter layers has been established, through which experiments of SAGD, nitrogen SAGP, flue gas SAGP have been conducted. According to the experimental results of temperature, pressure, production, water cut and the diversification of GOR curve, there exists mono layer breakthrough and steam overlay phenomenon in the thin and low permeability layer. But it does not cause greater impact on the development of steam chamber. After the injection of non-condensate gas, nitrogen and flue gas in the leading edge, it could not form a low temperature insulation band near the top and bottom of the oil reservoir. In contrast, the non-condensate gas would gather in the leading edge of the steam chamber, which prevents the horizontal expansion of the steam chamber and reduces displacement efficiency. The experimental results would provide important reference value for SAGD field experiments in super heavy oil reservoir with thin layers and inter layer.

Keywords - Extra heavy oil reservoir; Non-condensate gas push; SAGD; N_2; Flue gas; Physical simulation

I. INTRODUCTION

The technology on SAGP was firstly put forward by Butler research group [1]. They did a research on the mechanism of SAGP by adopting two-dimensional physical model during the period of 1998-2001, which proved that SAGP could decrease the heat loss of the steam chamber and receive a higher recovery ratio [2].

The SAGP technique initially succeeded in testing at the UTF oil reservoir experimental area of northern Alberta [3], Canada. In addition, many other programs like Burnt Lake and Pikes Peak achieved in mixing non-condensate gas [4]. In Liao He Oilfield, Block Du 84 heavy oil reservoir was experimented by injecting nitrogen gas. The average thickness of this experimental area is 112 meters. The experiment formed micro thermal non-condensate gas at the top of the reservoir, which cuts down the temperature of top bitumen on the process of steam injection into the oil reservoir and prevents the water from discharging prematurely in the field [5].

Most of the early studies agreed that the non-condensate gas could build a gas enrichment area between the reservoir and the area under the cap rock. The gas enrichment area would act as a heat insulator and reduce the heat loss [6]. Therefore, it helps to improve gas-oil ratio, whether the in-condensate gas is from dissolved gas or injection gas.

However, large number of reservoir simulation studies showed the non-condensate gas tends to assemble in the front of the steam [9-15], which reduces the temperature grade of the steam-front. By the way, the speed from heat to the cool area will be retarded. It will hinder the expansion of the steam chamber and reduce the production of oil.

There exists some coherence between the experimental results and numerical simulation results [7]. They proved the non-condensate gas plays a role of heat insulator and regulates the loss of heat transfer from steam dome to the cool oil area. The opportunity of the further expansion from the steam chamber to the reservoir and the recovery rate of the steam drives also can be cut down because of the non-condensate gas gathering near the gas oil horizon.

Whether the gathering place of the in-condensate gas has something to do with the reservoir thickness still remains uncertain at present. According to hundreds of experimental researches and field tests, the non-condensate gas is easier to gather on the top while the reservoir thickness is over 20 meters [8]. As for the SAGP mining way of heavy oil reservoir in a thin layer with low permeability, whether the non-condensate gas could act as a heat and decrease the heat loss to the overlying rock still needs an indoor physical simulation experiment. A further reorganization on the principles of expanding and the development effect of SAGP about the steam chamber are of great significance to direct the steam flooding of the heavy oil reservoir.

II. PHYSICAL MODEL FORMATION

A. Experimental Parameters Modeling

The proportion physical model study is based on the theory of similarity. There are two primary methods about SAGD physical model similarity criteria now: one is proposed by Butler research group [10]; the other one is the similar standard system proposed by Pujol and Boberg suitable for steam flooding [11]. The former is mainly used in two-dimensional physical model and the latter is applied both in two-dimensional model and three-dimensional model.

During the SAGP flooding process, because steam gas and non-condensate gas are injected at the same time, the physical model should consider the injection rate both of steam gas and non-condensate gas.

The SAGP technology is improved from the SAGD technology. So during the similarity criteria selection process, we should analyze the similar guidelines P of SAGD and consider the convergence issues in different exploit technology.

Adopting the similarity theory model [12] of Butler, considering the non-condensate gas injection, we sorted out the screening out similar guidelines. We recombined the steam injection rate, production time, permeability, which made the significance more specific.

TABLE I. EXPERIMENT MODEL PARAMETERS

Names	Unit	Reservoir prototype	Indoor model
well spacing	m	100	0.5
reservoir thickness	m	12	0.06
permeability (oil layer)	μm^2	2.57	207
permeability (inter layer)	μm^2	0.006	5
horizontal length of injector producer well	m	1000	0.042
porosity	%	27.5	36.2
initial oil saturation	%	64.6	80
reservoir temperature	℃	23	23
reservoir pressure	MPa	2.89～5.38	3.4
coefficient of thermal diffusion	m^2/s	4.1×10^{-7}	5.0×10^{-7}
crude oil viscosity in steam temperature	mPa·s	17.3	23.2
producing time		1.06 years	1.0 hour
steam injection rate		100m^3/d	30mL/min

B. *Experiment Device*

The process of SAGP is shown as Fig. 1. The core component is a two-dimension physical model of high pressure and temperature. The size is 500 mm×500 mm×40 mm, the most pressurization is 10 MPa and the highest temperature resistance is 350 °C. The assembled equipment physical model is laid in electrical heating jacket. Additionally, the injection system, control system, production system, and acquisition system are also included in the experimental apparatus.

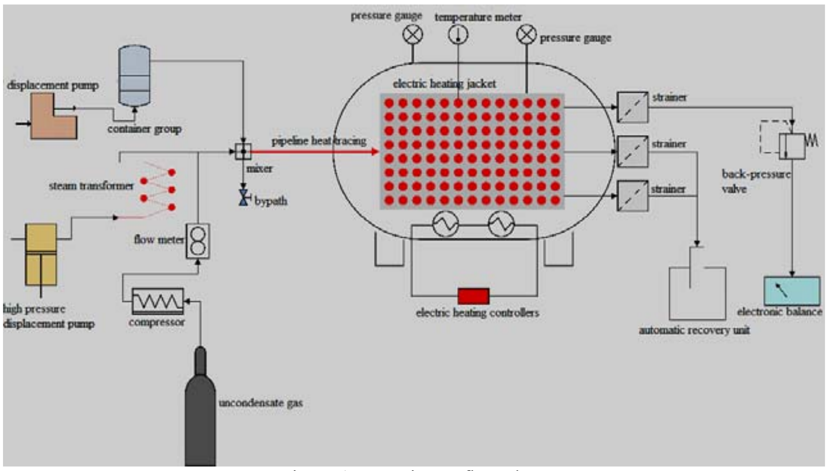

Figure 1. Experiment flow chart

The design of two-dimensional physical model is shown as Fig. 2. Because of the thinner thickness reservoir of convenience. The model depth will be enlarged from 6 cm to 12 cm. At the top and bottom of the reservoir, there are 2 horizontal wells. Specifically, the top of the reservoir is cap layer and the bottom of that is bottom layer. The upper simulation area, we use half of the full well spacing to simulate for experimental error minimization and operation horizontal well is 5 cm away from the cap layer and the lower horizontal well is 2 cm away from the bottom layer. Because of the low permeability shale inter layer laying at the top of reservoir, during the model designing and loading

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process, we should set a low permeability layer upon steam injection wells based on where the inter layer is. The depth of inter layer is 1 cm. It is on the top of the reservoir, and it is 3 cm from cap layer and 2 cm from horizontal wells. In this experiment, there are also 4 floors of 68 thermoplastic in the middle of reservoir to monitor the change of temperature filed. Meanwhile, there are 4 pressure measuring points in the middle of reservoir to monitor the change of pressure.

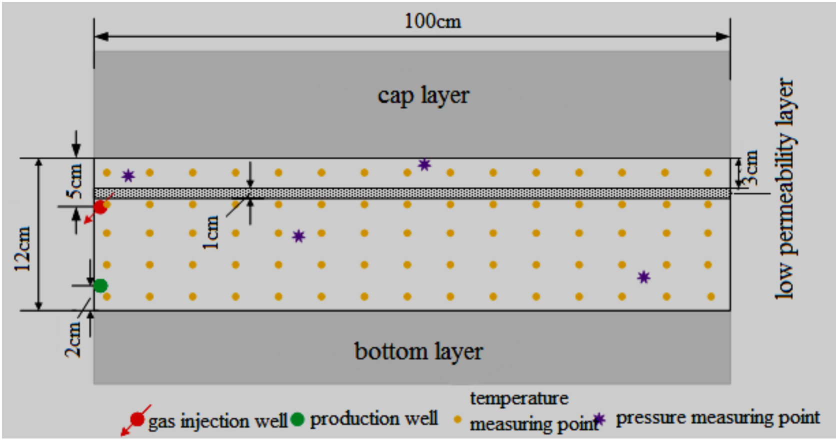

Figure 2. Schematic diagram of the physical model

C. Fluid Samples Preparation

We use the pot oil in well HQ1 as the experimental oil. We make the dehydration process before saturating, and the water cut is less than 1% after dehydration process. We adopted Huck rotational micrometer to test the viscosity and temperature. The viscosity is 42120 mPa·s when the temperature is 50℃. When the temperature increased to 100 ℃, the viscosity reduced to 864.5 mPa·s.

The total salinity is 2002 mg/L and the water is $NaHCO_3$ after analyzing the formation water.

There are two kinds of in-condensed gas in the experiment. The nitrogen is industry nitrogen and the purity is 99%. According to the flue gas in the field surrounding, there are N_2 in 85% and 15% in $C0_2$.

IV. Experiment Process

There are three experiments designed: the first group is pure steam assisted gravity drainage experiments (referred to SAGD experiment), the second group is nitrogen slug + steam assisted gravity drainage experiments (referred to nitrogen SAGP experiment), and the last group is flue gas slug + steam assisted gravity flooding experiments (referred to flue gas SAGP experiment). The purpose of three experiments is to simulate the effect of in-condensate gas to SAGD. We focused on the expansion law of steam chamber in the reservoir and analyzed the effects of thin inter layer to the steam chamber expansion during the experiment.

A. Establishing Thermal Communication between Wells

We use steam stimulation with steam injection rate of 30 mL/min and the dryness of 90%. Then we do the experiments

Flue gas SAGP experiment is consistent with the nitrogen SAGP experiment. The difference is that we replace the nitrogen slug into flue gas slug.

with two horizontal wells. We observed that the temperature changed between horizontal wells during the experiments. When the temperature reaches to 80℃ ~ 90℃ between wells, we think that the thermal communication has been established. We can do the SAGD experiments.

B. SAGD Simulation

Firstly, we do the SAGD experiment. After the establishment of thermal communication between wells, we inject steam in the upper horizontal wells and produce oil in the lower horizontal wells. We set up a back pressure on the well head of producing well. The pressure is equal to the reservoir pressure when steam stimulation is converted to steam driving. It shows the development process and pressure change process of temperature field in real time with the use of computer acquisition about temperature and pressure data for each measurement point. We use Erlenmeyer flasks to collect liquid at the export of experimental device. Then we could obtain the amount of oil, water cut, oil and gas ratio, recovery and other production of dynamic data at different time through oil-water separation measurement. The experiment was stopped when the instantaneous oil gas ratio of producing wells is less than 0.1 m^3/m^3.

The nitrogen SAGP experiment is based on the improvement of SAGD experiment. After the establishment of thermal communication between wells, we inject steam in the upper horizontal wells. Then we inject 0.1PV (underground) of nitrogen into the layer when the steam chamber is formed. We stop injecting pure steam until the instantaneous oil gas ratio of producing wells is less than 0.1 m^3/m^3, and then we stop the experiment.

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V. Experiment Results

A. *Development Features of Temperature Field*

During the SAGD experiment, the development process of the steam chamber is divided into three phases: steam chamber rising phase, steam chamber expansion phase and steam chamber decline phase, as is shown in Fig. 3.

The time of steam chamber rising phase is short, but the time of steam chamber horizontal expansion phase and steam chamber decline phase is longer. During the development process of steam chamber, because of the occlusion by a layer, there exists mono layer breakthrough. Due to the overlap features of steam, the development in upper part of the steam chamber is better than that in the lower reservoir.

With steam injection, the steam flow to the upper reservoir with the effect of overlap. Then it forms a steam chamber on the top of injection wells, as is shown in Fig. 3. At the same time, because of the occlusion by a layer, there exists mono layer breakthrough. It is different from the standard inverted triangle in homogeneous reservoir [16].

When the steam chamber reaches to the top of the reservoir, the steam chamber becomes horizontal extension, as is shown in Fig. 3. The steam chamber heats the surrounding reservoir by heat conduction. The oil viscosity decreases rapidly .The crude oil flows into production wells along oil gas interface because of gravity. It will be taken out together with the steam condensate in interface.

When steam chamber extends horizontally to the border of the top of oil layer. With the continued injection of steam, the steam chamber begins to slow down slowly, as shown in Fig.3. Finally, the top of the production well is filled with steam chamber, a lot of steam is recovered from the production wells and there exists a sharp decline in oil production. The water ratio rises sharply and the SAGD experiment ends.

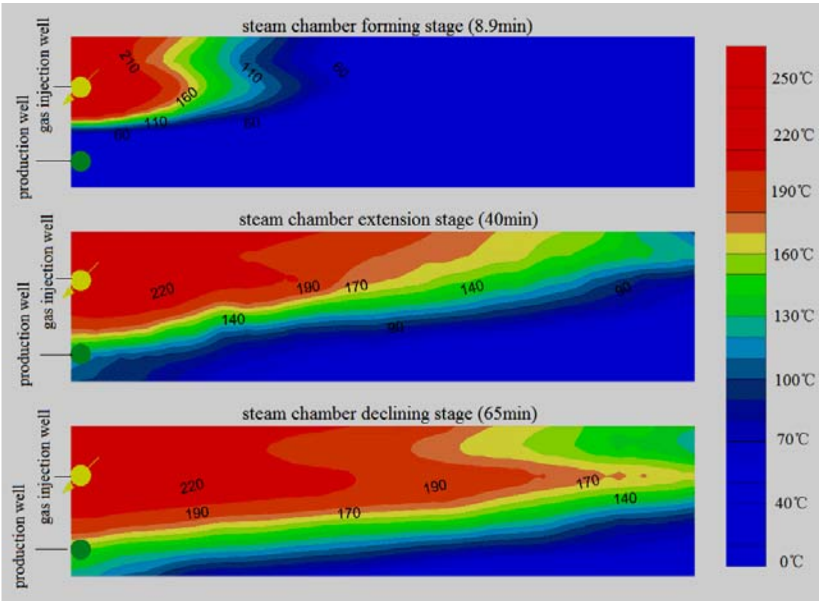

Figure 3 The steam chamber development of SAGD in different phases

Fig. 4 is a steam chambers developmental process in nitrogen SAGP experiment. There is a slightly difference with SAGD about steam chambers shape. The former is close to oval. The shape of steam chamber promoting is more uniform, but the advancing speed is slower than the latter. It showed that the nitrogen did not spread to the top of the reservoir to form an effective insulating layer after the nitrogen entering, but it decreased the heat loss. On the contrary, the nitrogen has always been displaced to the leading edge of the steam chamber by steam. Because the heat transfer coefficient of nitrogen at high temperature is lower than saturated steam, it hindered the expansion of the steam chamber in the leading edge and reduced the speed of the horizontal expansion of the steam chamber.

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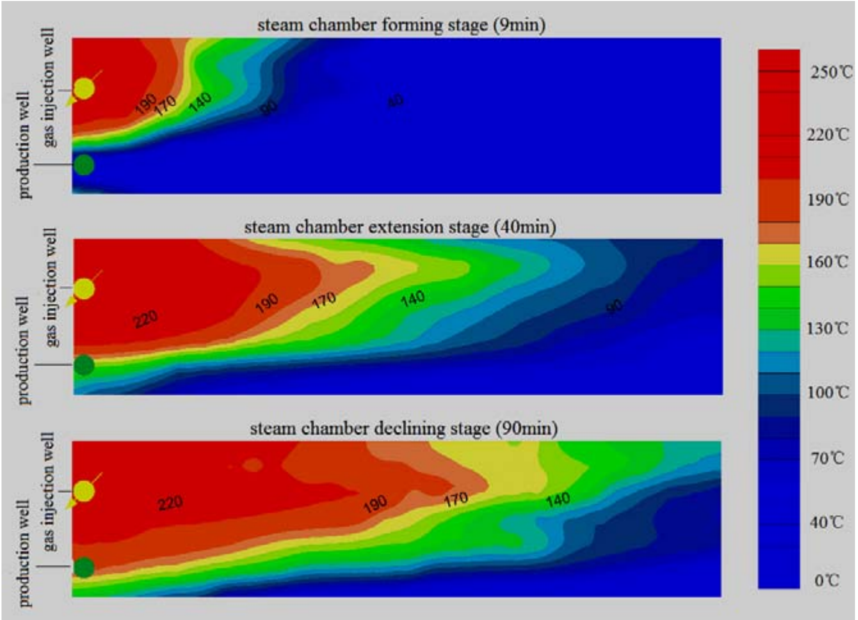

Figure 4 The steam chamber development of nitrogen SAGP in different phases

The morphology of the steam chamber developmental in flue gas SAGP is similar to nitrogen, as is shown in Fig. 5. Although there are still mono layer breakthrough nearby inter layer, the steam chamber development of flue gas SAGP is more uniform than pure steam SAGP and nitrogen SAGP. The speed of steam chamber extension is slower than the SAGD, and it is also slight slower than nitrogen SAGP. The main reason is that the flue gas is mixed with CO_2 (about 15%). At high temperature, the coefficient of thermal conductivity of CO_2 is lower than nitrogen and it is lower than the saturated water vapor. Therefore, the inhibition of the flue gas to plane thermal diffusion is slight stronger than nitrogen. The steam chamber is more uniform in the longitudinal direction.

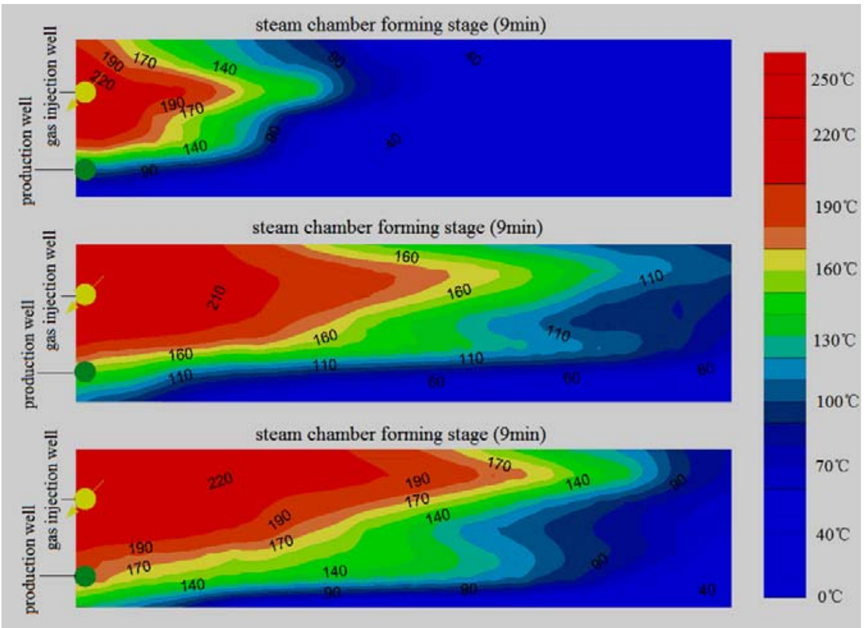

Figure 5 The steam chamber development of flue gas SAGP

B. Pressure Variation

In the two-dimensional physical model, the sequence of the four measurement points are P1、P2、P3 and P4 from left to right. As is shown in Fig. 6, form the pressure variation curve of SAGD, the pressure difference is about 0.05~0.26 MPa in the model. It shows that the mechanism of oil displacement in the process is the crude oil and condensate water drop relying on the gravity after the crude oil heating and viscosity reduction. In the vicinity of injection wells, it is the sooner the adequacy about the steam energy supplement, the faster and greater about the pressure rising, the sooner and the more about crude oil flush flow, the sooner and the lager about pressure decline. In the deep reservoir far away from injection wells, the steam effect is weak and the pressure is still close to the original pressure.

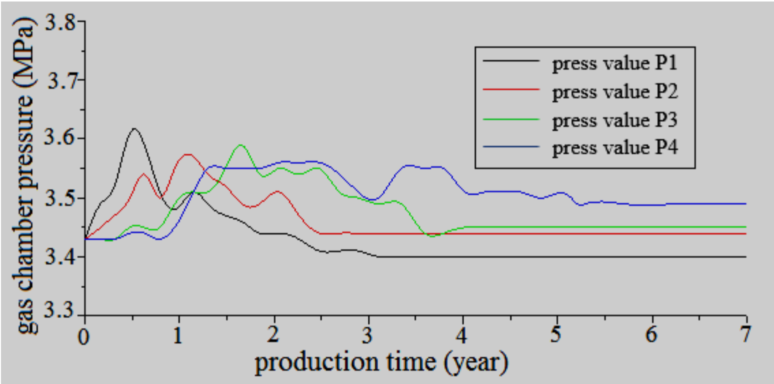

Figure 6 Pressure variation curve of SAGD.

In the nitrogen SAGP experiment, the pressure variation curve of the measurement points is shown in Fig. 7. With the injection of steam and nitrogen, the pressure increases in the steam chamber. As is shown in curve P1, the pressure increases from 3.44 MPa. After the steam spreading, the pressure reduces. About the measurement points far away from the steam chamber, with the injection of steam and nitrogen, the pressure increases. After the experiment, the pressure in the end of the model is higher than that in the entrance. During the total experiment, the pressure is about 0.05~0.38 MPa. Compared to SAGD, the pressure is higher obviously at the same time. The nitrogen injection plays the role of reservoir energy supplement.

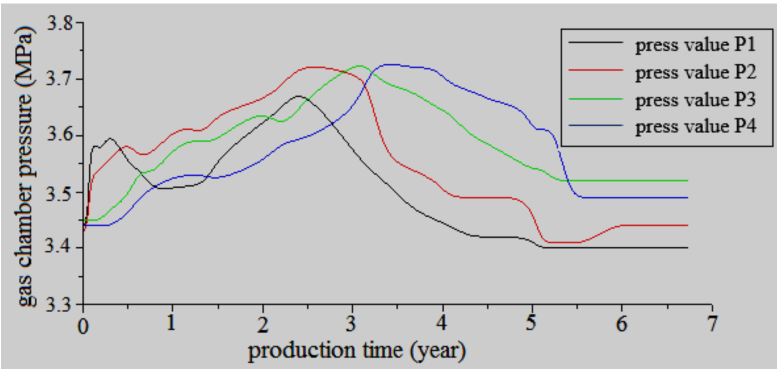

Figure 7 Pressure variation curve of nitrogen SAGP.

The pressure variation curve of flue gas SAGD is shown as Fig. 8. With the injection of steam and flue gas, the pressure of steam chamber increases rapidly, and the speed of rising is more rapid than nitrogen SAGD. The injection of flue gas plays the role to supply reservoir energy. The CO2 in it plays a role to the reduce viscosity.

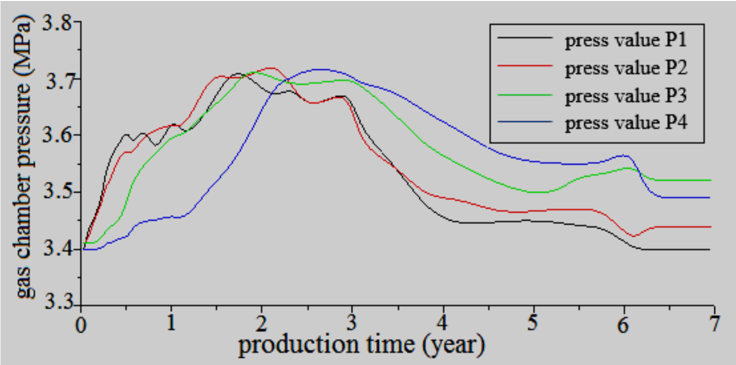

Figure 8 Pressure variation curve of flue gas SAGP.

C. *Variation of Oil-gas-water Output*

During the experiment of SAGD, the major characteristic of steam chamber forming stage is water content ratio decreasing sharply, as is shown in Fig. 9 to Fig.11. The SAGD water content ratio decreases from 93% to 81.6% at the beginning, then increases to nearly 91%. At this period the recovery percent is 4%. The water content ratio of nitrogen SAGP decreases from 66.1% to 58.3% at the beginning, then continually increases to nearly 69.1%. At this period the recovery percent is 14%.The water content ratio of flue gas SAGP decreases from 66.5% to 59.3% at the beginning. Then it increases to nearly 70.3%. At this period the recovery percent is 19.0%.

The steam begin to expand to the border when the steam overlays to the top of the reservoir. The crude oil flows to the horizontal production wells with gravity after heating and viscosity reducing, as is shown in Fig. 9 to Fig.11. The water content ratio of steam chamber extension stage is about 70％ and the degree of reserve recovery is 34.3~42%. The years of stable production are 3-5 years, which is the main oil production stage.

When the steam chamber expands to the border, it enters into steam chamber declining stage with the injection of seam, as is shown in Fig. 9 to Fig.11. The production reduces rapidly at steam chamber declining stage and the degree of reserve recovery is 5%~17.4％.

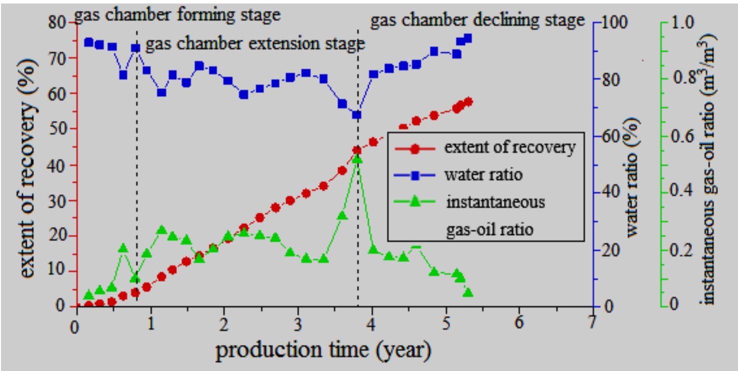

Figure 9 Production variation curve of SAGD

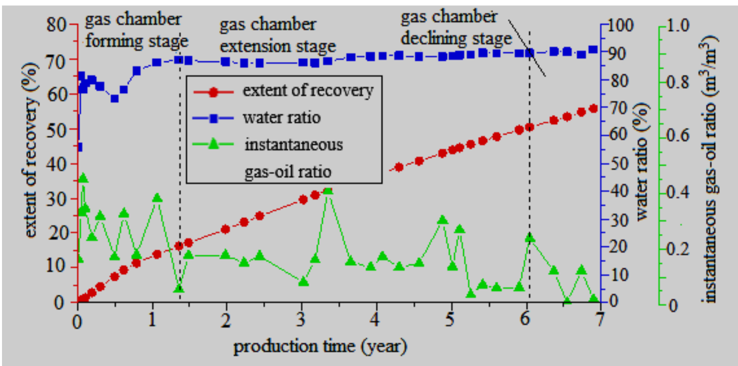

Figure 10 Production variation curve of nitrogen SAGP

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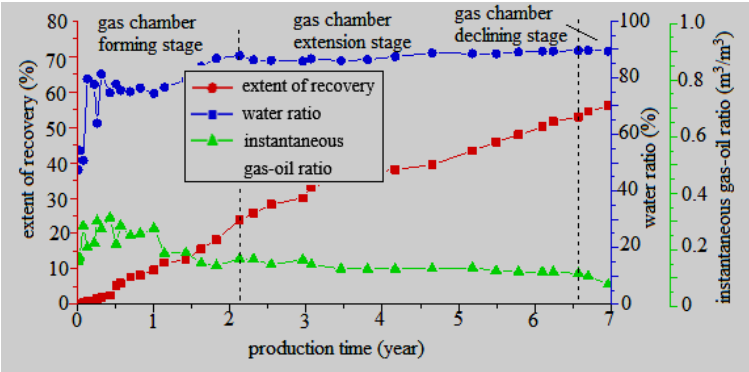

Figure 11 Production variation curve of flue gas SAGP.

The instantaneous is 0.1m3/m3. The ultimate recovery of SAGD is 55.7%. The producing time is 5.3 years. The cumulative oil/gas ratio is 0.199m3/m3. The ultimate recovery of nitrogen SAGP is 55.8%. The producing time is 6.9 years. The cumulative oil/gas ratio is 0.157m^3/m^3. The ultimate recovery of flue gas SAGP is 56%. The producing time is 6.96 years. The cumulative oil/gas ratio is 0.159m^3/m^3.

The formation time of each stage in SAGD is shorter than nitrogen SAGD and flue gas SAGD. Because of the obstruction of nitrogen and flue gas in the leading edge, the speed of steam chamber slows down, the producing time of nitrogen SAGD and flue gas SAGD extends, and the cumulative oil/gas ratio reduces obviously. The ultimate recovery increases slightly, but the magnitude is not great.

VI. CONCLUSIONS

(1) SAGD, nitrogen SAGP and flue gas SAGP experiment prove mono layer breakthrough and steam overlay phenomenon in the thin and low permeability layer. But it does not cause greater impact on the development of steam chamber.

(2) For thin Super Heavy Oil Reservoirs, during the nitrogen SAGP and flue gas SAGP experiment, it could not form an effective non-condensate gas reservoir near the top and bottom of the oil reservoir. It could not play the role of thermal insulation. In contrast, most of the non-condensate gas would gather in the leading edge of the steam chamber to form a heat-insulation area between the steam and cold oil. It prevents the horizontal expansion of the steam chamber and it is not good for steam chamber to heat the crude oil of deep layer.in the equal time, it leads to the drop of degree of reserve recovery.

(3) The non-condensate gas can gather to the top of oil reservoir and form an effective insulation layer may relate to the steam injection speed, injection pressure, injection rate, reservoir thickness and so on. Furthermore, more experiments, numerical simulation and field tests are used to verify it.

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