Investigation of the Features About Steam Breakthrough in Heavy Oil Reservoirs During Steam Injection

Dong Xiao-Hu* and Liu Hui-Qing

MOE Key Laboratory of Petroleum Engineering, China University of Petroleum, Beijing, 102249, China

Abstract: With the further exploitation of heavy oil reservoirs, steam breakthrough blocks are seen in more and more areas and pose increasing damage. Based on the qualitative understanding of the formation mechanism of steam channeling, the concepts of steaming time and heat invading volume are introduced. After that, the geological models of steam injection of heavy oil reservoirs are established. We describe the sensitive factors affecting the steam channeling in a relatively accurate manner and mainly study the influence of several parameters on steaming time and heat invading volume. The results present that the possibility of steam channeling is higher and the time it takes is shorter when the permeability is greater, viscosity higher, depth shallower, steaming strength bigger and layer looser. Orthogonal design results show that the k-values of permeability on steaming time and heat invading volume are 7.43, 19.0 respectively, it has the most significant influence on two indicators.

Keywords: heavy oil reservoir, steam injection, steam breakthrough, orthogonal design.

1. INTRODUCTION

Heavy oil occupies a large share of world oil and gas resources. Considering its high viscosity property and non-Newtonian flow character at low temperature, thermal recovery is always the main exploitation way for heavy oil reservoirs [1-3]. Because of the iterative stimulation of high strength steam, during the process of oilfield producing, oil layers are heated chronically, and formation skeleton structure is also damaged, leading to a massive sand production. Thereafter, the reservoir porosity and permeability are changed substantially; meanwhile the water cut of producers is also varied [4-6]. Especially for the loose reservoirs (the weak cementation sand stone reservoir), after a long-term production of heat injection, rock is deformed seriously and sand produced severely. Then a lot of large pore paths are established. Most of the injected steam enters into these higher permeable paths and penetrate into the producer earlier. The injected heat flow out of the steam channeling wells directly. Oil layers can not be heated sufficiently, resulting in a lower heat efficiency and a smaller sweep volume. Finally, the normal exploitation of blocks and wells are also influenced.

There have been a number of literatures which reported about steam breakthrough. Doscher *et al*., [7-8] investigated the effect of oil viscosity and reservoir thickness on steamdrive efficiency. Because of the overlapping of steam, it will flow through the reservoir across the top of the oil column once steam injection is conducted. It is therefore a smaller oil/steam ratio and a higher recovery will be achieved in a thinner reservoir. Based on the description of tracer breakthrough from the five-spot pattern as well as other common flooding patterns, Yuen [9] and Brigham [10] made an explanation to the reservoir heterogeneity utilizing the tracer profile between wells. It benefits the description and prediction of high-permeability region between injectors and producers. With the assumption of a cylindrical cross-section and steam zone growth limited by heat losses, Closmann [11] established a model to predict the channel size from the time of steam breakthrough at a producer. Later, with the development of well logging technologies, the study of steam breakthrough achieved a considerable opportunity. In the past, both temperature and dual-spaced neutron (DSN) tools have been used to identify steam breakthrough zones with limited success. Based on these approaches, Masse *et al*., [12] did some improvement, and proposed the pulsed-neutron capture logs (PNC) to indentify the steam breakthrough zones. The use of PNC technique allows easy and confident to determine the steam saturation in a stacked sand/shale sequence. Thereby, to make a deeper study of steam breakthrough has become significant in practice.

This paper introduces two steam channeling parameters which facilitate the description of the speed and strength of steam channeling between wells. Based on that, it analyzes the sensitive factors affecting the steam channeling in a relatively accurate manner, and conducts an orthogonal test plan.

2. DETERMINATION OF THE STEAM CHANNELING PARAMETERS

After steam is injected into the reservoirs, a similar orbicule with high pressure will be primarily formed at the bottom of well [13]. With the continuation of steam injection, the pressure of orbicule goes up, and the steam at a high-pressure status will penetrate into the weak place of reservoir with a high permeability. Following steam

*Address correspondence to this author at the No. 18 Fuxue Road, Changping District, Beijing, China. Postcard: 102249;
Tel: 010-8973. 1163; E-mail: donghu820@163.com

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breakthrough, therefore a banded steam flowing (the shape of steam flowing is a banded region) will buildup in reservoir. Due to the iterative stimulation of steam, the banded steam flowing is growing, and at the same time the oil recovery is enhanced. Then steam breakthrough will take place following the connectivity of the flows of two adjacent wells.

The reasons of the occurrence of steam breakthrough are shown below: The move of weakly consolidated grain; the large density of well pattern; the overlapping of steam; the thermal cracking of asphalt; the dissolving of mineral grain and cement; the irrational employment of injection parameters etc [5-6, 14]. beyond that, the existence of tiny fracture, the high viscosity of crude oil, the low quantity of cement, the out-sync of injection and production between the adjacent wells, the changes of tectonic stress field and the slant of oil layers could also induce the steam breakthrough.

In order to quantificationally describe the speed and strength of steam channeling, we introduce the concepts of steaming time and heat invading volume. During the process of huff and puff in heavy oil reservoirs, steam breakthrough is often not happened between wells, instead of the severe overlapping of steam in the thick layers. It results from the intense heterogeneity of reservoirs. After converting into the steam flooding, because of the consecutive injection of steam, the steam front is advancing. When it comes to the producer, the temperature of the bottom will suddenly rise. In other words, the temperature will emerge a breakpoint. The time when the breakpoint emerged can be called the steaming time, as Fig. (**1**) shown. This parameter could be used to depict the speed problem of steam channeling. Heat invading volume is a physical parameter to describe the degree of steam channeling. It is the total pore volume between the wells under the steaming time where the temperature is above the temperature of the bottom of producers. Generally speaking, the non-dimensional heat invading volume is recommended for convenience, which is the ratio of heat invading volume and total pore volume.

3. NUMERICAL MODELS AND SENSITIVITY ANALYSIS

The STARS module of CMG software is used to establish these models. In the models, sand production is achieved in a form of reaction dynamic equations (One unit of free sand can be produced by one unit solid sand at certain conditions). By means of the reaction equations, the original solid sand became the free sand at a certain sand producing rate. When we determine the sand producing rate and the content of original solid sand, the sand production could be simulated.

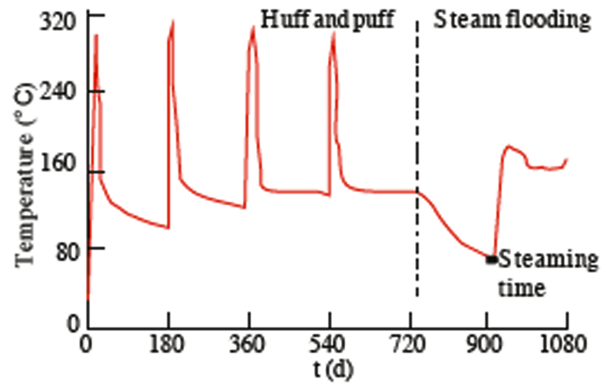


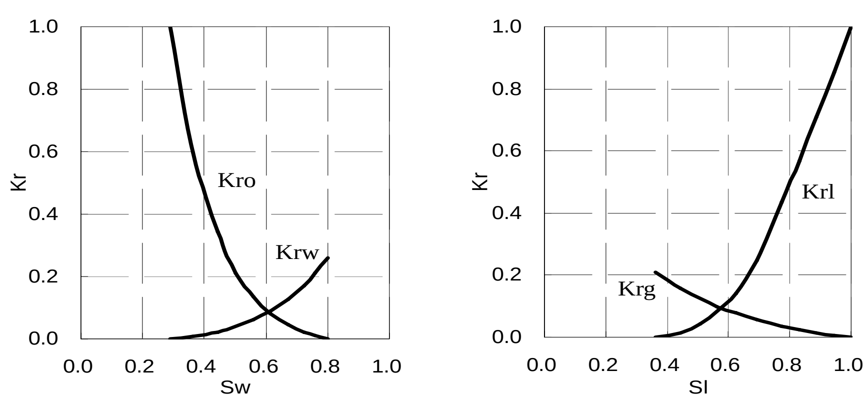
Fig. (1). The temperature profiles of the bottom of producer .

3.1. Design of the Parameters

By the use of the typical parameters of Jinglou blocks in Henan oilfield (located at Nanyang, in Henan province, China), Sinopec, we establish the conceptual models to study the influences of reservoir, fluid and injection-production parameters. The middle depth of oil-layers is 900m. The well distance is 140m. The porosity and permeability are 30%, $2000\times10^{-3}\mu m^2$ respectively. The original temperature of oil-layer is 48℃. The effective thickness is 4m. This group undergoes steam stimulation for four periods firstly. At the stage of huff and puff, every well is injected steam for 10 days; soaks for 2 days and manufactures for half a year. The steam injection rate is $200m^3/d$ at the first period. Then it will increase at 10% per period in the later three ones. After stimulation for four periods, the heat connection is achieved, and then the group will convert into steam flooding. During this process, the production-injection ratio is set to 1.2. Steam injection strength is 1.6 t/(d·m·ha). The relative permeability curves are shown in Fig. (**2**).

3.2. Sensitivity Analysis

The factors which influence the occurrence of steam breakthrough include the internal geological factors and the exterior exploitation factors (also called artificial factors) [5,



***a.* curves for oil & water** ***b.* curves for gas & liquid**

Fig. (2). Relative permeability curves.

15]. Geological factors comprise: the degree of deposit and compaction, the heterogeneity of fluid and reservoir etc. Exploitation factors comprise: the parameters of injection and production, the well pattern and distance etc.

3.2.1. The Influence of Permeability

The heavy oil reservoirs give priority to the contact cement. The amount of cementation matter is low, and the clay cementation is contained. This reservoir has a high porosity and permeability. Larger permeability reservoirs have larger flowing velocity. Meanwhile the phenomena of steam channeling will become more serious. In these models we calculate the steaming time and heat invading volume under different reservoir permeability. The comparison results are shown in Fig. (**3**).

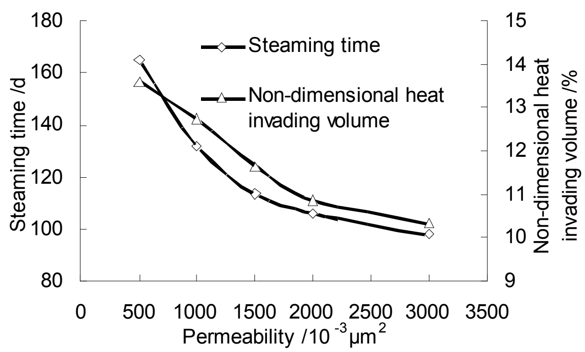


Fig. (3). The influence of permeability on steam breakthrough.

The obtained results present that the steaming time and heat invading volume decrease with the increase of reservoir permeability. The flowing capacity will be better in a higher permeable reservoir. Then the breakthrough of inter well will be much easier. Finally, the steaming time and the heat invading volume will diminish.

3.2.2. The Influence of Oil Viscosity

Due to the high viscosity of heavy oil, the migration of sand grain gives priority to friction and carrying. At the same time, the high viscosity oil could also prevent the settlement of grain in the migration process. The grain will be distributed within the crude oil evenly. They can produce with the liquid. It has helped to the formation of channeling circulate. In this part, using five viscosity-temperature curves, we simulate the influence of crude oil viscosity on steam breakthrough. Results are shown in Fig. (**4**).

Along with the rise of oil viscosity, the oil/water mobility ratio is increasing. As a result, the viscosity fingering becomes more serious. Steam breakthrough will be easier to happen. Finally, steaming time shortens, and heat invading volume diminishes. Compared with permeability, the influence of oil viscosity on steam breakthrough is lower.

3.2.3. The Influence of Reservoir Depth

Larger depth has higher reservoir pressure and temperature. By the method of numerical simulation, to employ the same injection-production parameters, we study the influence of strata depth on steam breakthrough. Results are presented in Table **1**. From this table, we can see that the steaming time and heat invading volume have a slight increase with the rising of reservoir depth. The influence of reservoir depth on steam breakthrough is lesser.

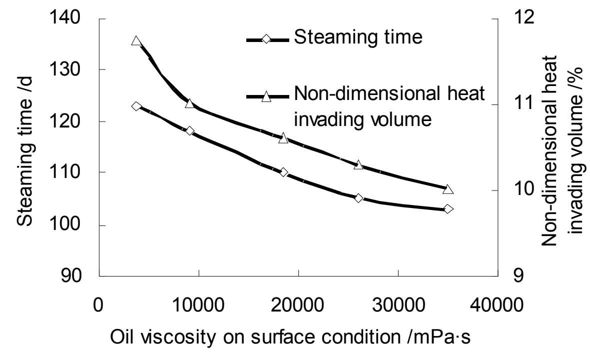


Fig. (4). The influence of oil viscosity on steam breakthrough.

Table 1. The Influence of Strata Depth on Steam Breakthrough

T-Depth (m)	Steaming Time (d)	Non-Dimensional Heat Invading Volume (%)
300	115	9.83
600	118	9.91
900	121	10.05
1200	124	10.96
1500	131	11.88

3.2.4. The Influence of Steam Injection Strength

As an essential parameter for steam injection projects, Steam injection strength is defined as the amount of steam injected per unit thickness and unit area of oil layers in unit time. Bigger steam injection strength results in poorer strata stability. Also the flow velocity is rising. The steam injected wash against the oil layer, and a larger channeling circulate will be created. Finally the phenomenon of steam breakthrough is intensified. In these models, we set the injection-production ratio 1.2. To alter the model steam injection strength, we could obtain the relation between strength and steam breakthrough. Fig. (**5**) presents the simulation results. With the increase of steam injection strength, the drawdown pressure between injection-production wells is gradually rising. Flow quantity is increasing. The temperature and hot water will get to the producer quickly. Finally steaming time and heat invading volume will diminish.

3.2.5. The Influence of Cementation Degree

Cementation degree is a non-dimensional physical parameter to describe the consolidation degree of rock particle and tuff fillings. Cementation degree is determined by the variation rate of porosity and the relation of porosity–permeability. A higher value of cementation degree has a faster rate of porosity variation. The reservoir is looser, and the variation of permeability is also greater. The formation of channeling circulate is easier. Fig. (**6**) shows the simulation results. With the rise of value, the cementation degree will weaken. Then the channeling circulate could be formed in short times. The steaming time will shorten. Meanwhile weak cementitious reservoir will lead to more serious sand production. The heat invading volume will increase.

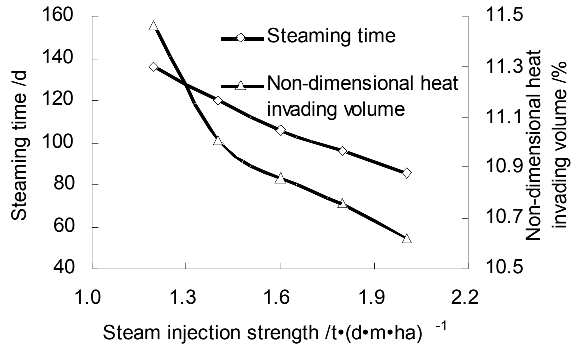


Fig. (5). The influence of steam injection strength on steam breakthrough.

3.3. Design of Orthogonal Test

Orthogonal design, also called orthoplan, is one of the most popular methods of test designation to scientifically arrange and analysis the multi-factorial test utilizing the orthogonal table [16]. In comparison with tornado chart, The advantages of orthogonal test are shown in the following aspects: (1) uniformly pick out the representative plans among the whole tests; (2) seek the optimal case which usually beyond the text plans through the analysis of test results; (3) achieve more information out of the test results, such as the importance and influencing tendency of each factors on the test results. According to the simulation results above, we establish an orthogonal test plan ($L2_5(5^6)$). By the method of differential analysis and variance analysis, we study the synthetical influence of different parameters on steam channeling. That includes: the reservoir permeability, the oil viscosity, the reservoir depth, the steam injection strength and the cementation degree. The levels we designed are shown in Table **2**.

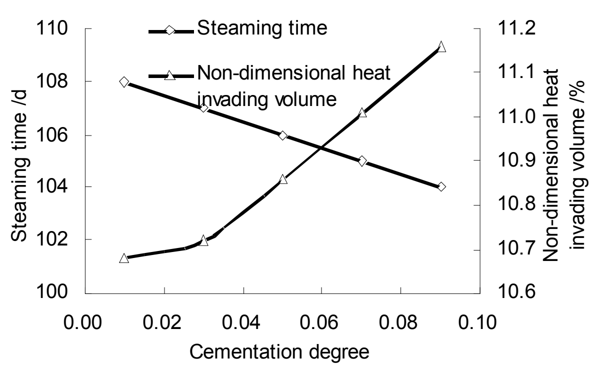


Fig. (6). The influence of cementation degree on steam breakthrough.

3.4. Results Analysis

In order to create a unified criterion, we employ the steaming time and non-dimensional heat invading volume as the two evaluation indicators. Using the method of intuitive differential analysis, we could obtain effect sequence of each sensitive factor. The simulation results are shown in Table **(3, 4).** For steaming time, the effect sequence is: Permeability > steam injection strength > oil viscosity > cementation degree > reservoir depth. For non-dimensional heat invading volume, the effect sequence is: Permeability > reservoir depth > oil viscosity > steam injection strength > cementation degree.

Table 2. The Parameters Table of Orthogonal Test Plan

Level	Factor				
	Perme-ability ($10^{-3}\mu m^2$)	Oil viscosity on S.C. (mPa·s)	Reser-voir depth (m)	Steam injection strength ($t\cdot(d\cdot m\cdot ha)^{-1}$)	Cementa-tion degree (decimal)
Level 1	500	3789	300	1.2	0.01
Level 2	1000	9136	600	1.4	0.03
Level 3	1500	18537	900	1.6	0.05
Level 4	2000	27128	1200	1.8	0.07
Level 5	3000	35426	1500	2.0	0.09

Table 3. The Influence of Different Factors and Levels on Steaming Time

Factor	Perme-ability	Oil Viscosity on S.C.	Res-ervoir Depth	Steam Injection Strength	Cementa-tion Degree
K1	152.6	125.0	129.6	137.2	118.8
K2	129.6	106.0	120.8	141.0	109.4
K3	115.4	107.6	107.2	133.6	133.6
K4	102.6	115.4	115.0	113.0	111.8
K5	94.8	141.0	122.4	85.8	121.4
R	57.8	35.0	22.4	55.2	24.2

Where, Ki = Sum (Steaming time ji)/N; i, representing the level of factor (1, 2…5); j, representing the factor (Permeability, Oil viscosity on S.C.… Cementation degree); N is the amount of levels (5); R =Max (Kj)-Min (Kj).

Table 4. The Influence of Different Factors and Levels on Non-Dimensional Heat Invading Volume

Fact or	Perme-ability	Oil Vis-cosity on S.C.	Reser-voir Depth	Steam In-jection Strength	Cementa-tion Degree
K1	16.09	12.72	12.78	12.10	12.45
K2	12.94	12.07	12.01	13.48	12.37
K3	12.02	12.40	11.79	12.49	13.51
K4	12.56	12.90	13.49	13.36	12.32
K5	10.00	13.51	13.53	12.18	12.97
R	6.09	1.44	1.74	1.37	1.18

Table 5. The Results of Variance Analysis

Factor	Permeability		Oil Viscosity on S.C.		Reservoir Depth		Steam Injection Strength		Cementation Degree		Error	
	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2
Sum of deviation square	10544	96.5	4160	5.9	1412	13.1	9772.0	8.6	1815	5.2	1419	5.1
Degree of freedom	4	4	4	4	4	4	4	4	4	4	4	4
Mean square	2636	24.10	1040	1.480	353.0	3.280	2443	2.140	453.7	1.290	354.7	1.270
F-Value	7.43	19.0	2.93	1.16	0.99	2.58	6.89	1.68	1.28	1.01		
Significance	Y	Y	N	N	N	N	Y	N	N	N		

Where, Y, representing the influence of this factor on this index is significant; N is opposite.

Differential analysis could not settle the influence of test error on the results. So we can not judge whether the differences of simulation results come from the different factors and levels or not. The test error may also have an effect on the results which could not be distinguished by this intuitive method. On the contrary, the variance analysis is able to settle this problem. It could make up the defect of differential analysis. Therefore, we respectively conduct variance analysis on steaming time (index No. 1) and non-dimensional heat invading volume (index No. 2). Table **5** shows the results. The test level (a) is set as 0.05. According to the level table of significance test, we could find that the value of $F_{0.05}(4, 4)$ equals 6.39. Results indicate that the influence of permeability on the two indicators is the most significant. Then, the influence of steam injection strength on steaming time is significant. In addition, the influence of other factors on these two indicators is not prominent.

4. CONCLUSIONS

1. To establish the geological models of steam injection of heavy oil reservoirs, the influence of permeability, viscosity, depth, steam injection strength and the cementation degree on steaming time and heat invading volume is discussed by the method of single factor analysis. The obtained results present that the possibility of steam channeling is higher when the reservoir permeability is greater, oil viscosity higher, depth shallower, steaming strength bigger and oil layer looser.
2. Based on the orthogonal test plan, we conduct the differential analysis; the effect sequence of different factors is achieved. For steaming time, the effect sequence is: Permeability > steam injection strength > oil viscosity > cementation degree > reservoir depth. For non-dimensional heat invading volume, the effect sequence is: Permeability > reservoir depth > oil viscosity > steam injection strength > cementation degree.
3. In order to eliminate the influence of test error, we conduct a variance analysis. From the results, we found that the influence of permeability on the two indicators is the most significant. Then, the influence of steam injection strength on steaming time is significant. In addition, the influence of other factors on these two indicators is not marked.

Field Units Conversion Factors

mPa•s × 1.0 * E+00 = cp

℃ × 9/5+32 = ℉

m × 3.048 * E-01 = ft

ha × 1.076 391 * E-02 = sq ft

m^3 × 6.289 811 * E+00 = bbl

t × 4.535 924 * E-04 = lb

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CONFLICT OF INEREST

None declared.

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