The Role Analysis of Superheated Steam Injection to Improve Performance in Thin Heavy Oil Reservoir

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Abstract—**Superheated steam has some special properties, such as high temperature but low pressure, high quality (100%), higher latent heat and larger specific volume. In this article, numerical simulation technology was employed to analyze performance of cyclic superheated steam stimulation in thin heavy oil reservoirs with different net pay, such as 1-3 m, 3-5 m and 5-10 m. By contrasting of incremental oil production, saving volume of steam consumption, distribution features of reservoir temperature and oil saturation after injecting conventional wet steam, hot saturated steam and superheated steam, the technological advantages of cyclic superheated steam stimulation was analyzed to develop heavy oil reservoirs. The results showed that incremental oil ability of superheated steam was much higher than conventional wet steam and hot saturated steam, but the degree of incremental oil gradually became slower when superheated degree was over 20 ^{o}C. When the same volume of heavy oil was produced by the three kinds of steams, superheated steam could save steam consumption.**

Index Terms—**superheated steam; heavy oil reservoir; cyclic steam stimulation; EOR; numerical simulation**

I. Introduction

In the last few decades, steam injection has been recognized as an important method to develop heavy oil reservoirs.[1] Current interest in steam injection method is toward the use of superheated steam, which presents higher temperature at the same pressure. The technology of superheated steam injection has been applied in some heavy oil reservoirs, such as Henan Oilfield in China and Pre-salt reservoir of Kenjiyak Oilfield.[2] [3] Superheated steam is a kind of special steam whose temperature is above the corresponding saturated temperature at a given pressure. Compared with the conventional wet steam, superheated steam has some characteristics, such as elevated temperature, high quality, low pressure, large specific volume and etc.[4] Therefore, there are some obvious differences between superheated steam and saturated steam to development heavy oil reservoirs. Many experimental results showed that superheated steam could prompt some physical and chemical changes of minerals and fluids in heavy oil reservoirs to result in a large reduction of oil viscosity or flow resistance.[2]-[4] In this article, based on the analysis of EOR mechanisms, the technology of numerical simulation was employed to study technology advantages and performance characteristics of cyclic superheated steam stimulation in heavy oil reservoirs.

II. Recovery Mechanisms

Superheated steam is water phase at a special state. The recovery mechanisms can be summarized as following.

- *Viscosity reduction:* The viscosity of heavy oil is very sensitive to temperature. High temperature largely reduces the viscosity of heavy oil to result in decreasing flow resistance in reservoirs.[5] Therefore, viscosity reduction is the most important mechanisms during superheated steam injection.
- *Distillation effect:* Superheated steam is at a state of high temperature but low pressure. Therefore, superheated steam can obviously increase distillation efficiency of crude oil, especially heavy oil.[6]
- *Thermal expansion:* The thermal expansion degree of heavy oil and rock minerals is larger under higher temperature and heat during superheated steam injection.[2]-[5]
- *Hydrothermal cracking:* Heavy oil occur a series of chemical reactions, such as desulfurization, denitrogenation, hydrogenation. The hydrothermal cracking reactions largely decrease heavy oil viscosity, reduce the content of sulfur, oxygen and nitrogen in heavy oil to improve its flow ability in porous media.[7]
- *Plugging removal:* A flushing effect from high speed steam can effectively remove drilling fluid

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pollution near well bore. The plugging material can be produced along with hot oil, steam and condensate water during production to decrease flow resistance near well bore.[7]-[9]

Emulsification flooding: Light distillate of heavy oil generates oil-in-water emulsion or water-in-oil emulsion in the front of steam condensate in reservoirs. [10] [11] The viscosity of oil-in-water emulsion is larger than water and the viscosity of water-in-oil is larger than oil. Therefore, the flow resistance gradually increases in higher permeable formation to decrease steam fingering and improve steam sweep efficiency in reservoirs.

III. Production Performance Analysis

A. Basic Parameters

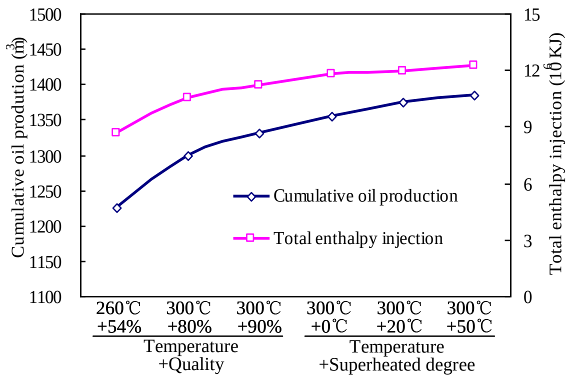
According to the geological characteristics, such as, shallow depth, thin thickness and high viscosity, in Henan Oilfield, a series of reservoir parameters were chosen for numerical simulation in this article. The reservoir depth was 220 m. The net pay was respectively chosen 1.8 m, 4.2 m and 6.0 m. The absolute permeability was $1250\times10^{-3}\mu m^2$. The porosity was 31%. The initial oil saturation was 65%. The initial reservoir temperature was 26 ^oC. In order to simulate distillation effect of crude oil, oil component was split light oil, medium oil and heavy oil, as listed in Table I. During numerical simulation, wet steam was injected into reservoirs in the first cycle and then superheated steam was injected into reservoirs from the second cycle. The steam quality was chosen 54% for wet steam at 260^oC. The higher quality 80% for higher temperature of wet steam at 300^oC. The superheated degree was respectively chosen 0.0, 20.0 and 50.0^oC for superheated steam at 300 ^oC. [12]

TABLE I. Type Sizes for Camera-Ready Papers

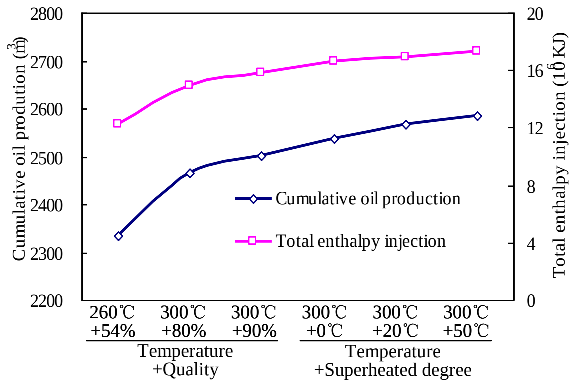
Components / Properties	Water	Light oil	Medium oil	Heavy oil
Molal weight (kg/mol)	0.018	0.030	0.150	0.300
Mass density (kg/m^3)	1000.0	821.0	903.0	976.0
Critical pressure (MPa)	22.048	3.551	1.965	0.00
Critical temperature (^oC)	374.15	90.0	250.0	0.0
Volatilizable (yes or no)	yes	yes	yes	no

B. The Analysis of Oil Production

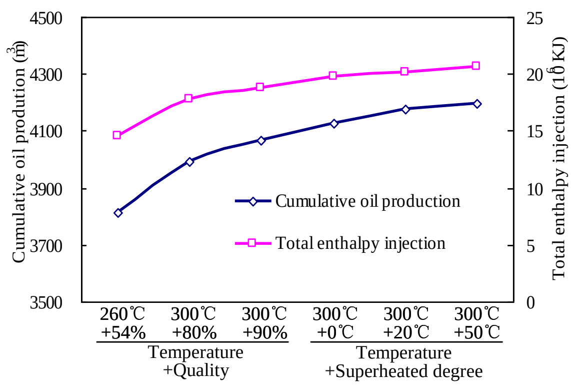
According to the range of net pay in Henan Oilfield, thin heavy oil reservoir was classified three cases, such as 1-3m, 3-5m and 5-10 m. The incremental oil ability was analyzed for wet steam and superheated steam to compare the cumulative oil production of 260^oC wet steam, 300^oC wet steam and different superheated degree of superheated steam. For thin heavy oil reservoirs with different thickness, the cumulative oil production of superheated steam is obviously higher than wet steam, as shown in Fig. 1. The cumulative oil production gradually increases as superheated degree or steam quality increases. For superheated steam injection, the cumulative oil production basically linearly increases as superheated degree increases. The results show that the incremental oil ability of superheated steam gradually increases as superheated degree increases, as shown in Fig. 1 (d). The degree of incremental oil is larger for thinner net pay, which presents superheated steam has a certain advantage in thinner heavy oil reservoirs. The reason lies in higher temperature and quality of superheated steam. The temperature of oil reservoirs is higher during cyclic superheated steam stimulation than cyclic wet steam stimulation. The difference of oil production is larger more and more as the stimulation cycles increases. Meanwhile, the volume of steam chamber is larger for superheated steam than wet steam under reservoir conditions, which shows that the swept volume of superheated steam is larger during injection stage. [2]



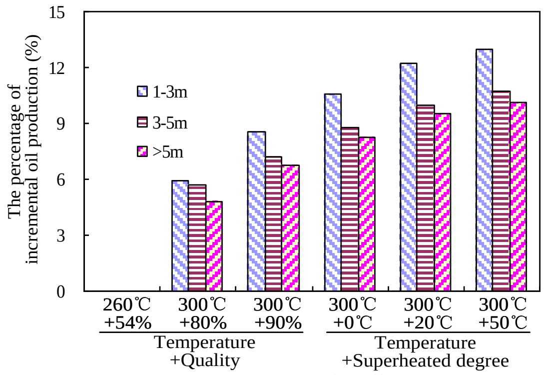
(a) 1-3m net pay



(b) 3-5m net pay



(c) 5-10 m net pay

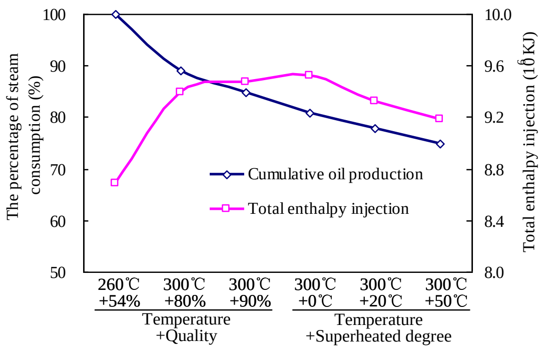


(d) Incremental oil percentage for different net pay

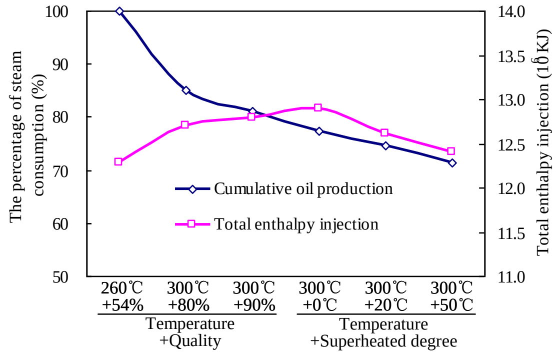
Figure 1. The results of incremental oil ability for different net pay

C. The Analysis of Steam Saving

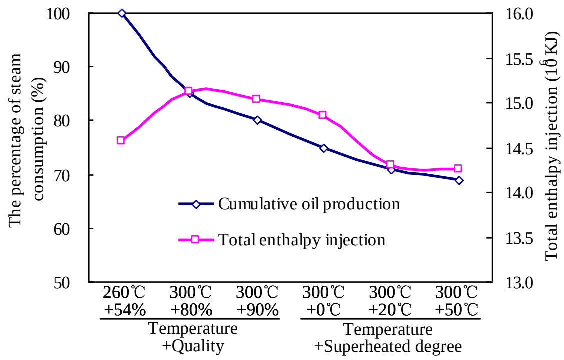
Based on the oil production of wet steam with quality of 54% at 260^{o}C, numerical simulation was employed to study the amount of steam injection to achieve the same oil production for different steam, such as wet steam with quality of 54% at 260^{o}C, wet steam with quality of 80% at 300^{o}C, superheated steam with superheated degree of 0^{o}C, 20^{o}C and 50^{o}C at 300^{o}C. For 1-3 m heavy oil reservoirs, if the amount of steam consumption was regarded as 100% for wet steam with quality of 54% at 200^{o}C, the amount was 89% for wet steam with quality of 80% at 300^{o}C, and the amount are respectively 81%, 78% and 75% for superheated steam with superheated degree of 0^{o}C, 20^{o}C and 50^{o}C at 300^{o}C (superheated steam temperature), as shown in Fig. 2 (a). Fig. 2 (b) tells us that the amount of steam saving are respectively 15.0%, 22.5%, 25.5% and 28.5% for different steam, such as 80 % wet steam at 300^{o}C, dry steam (superheated degree of 0^{o}C) at 300^{o}C, superheated steam with superheated degree of 20^{o}C and 50^{o}C at 300^{o}C in heavy oil reservoirs with net pay of 3-5 m. Fig. 2 (c) tells us that the amount of steam saving are respectively 15%, 25%, 29% and 31% for different steam in heavy oil reservoirs with net pay above 5 m. Therefore, the cumulative steam injection of cyclic wet steam stimulation is far greater than cyclic superheated steam stimulation at the same oil production. The amount of steam injection gradually decreases with steam quality or superheated degree increases, as shown in Fig. 2 (d). The percentage of steam consumption decreases as net pay increases, which presents that the thermal efficiency is higher for high quality wet steam or superheated steam in heavy oil reservoirs with the same net pay.



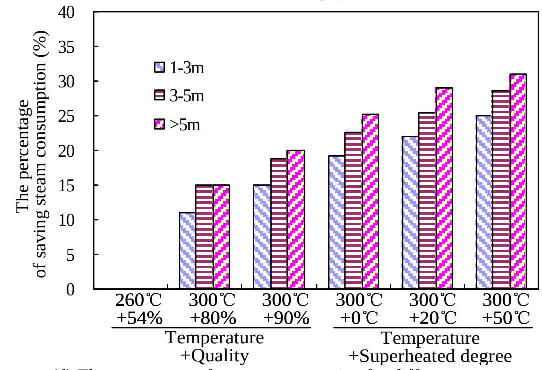
(a) 1-3m net pay



(b) 3-5m net pay



(c) 5-10 m net pay



(d) The percentage of steam consumption for different steam

Figure 2. The results of steam consumption for different net pay

D. The Analysis of Reservoir Properties

The distributions of reservoir temperature are shown in Fig. 3. The results show that the heating area of superheated steam is obviously larger than wet steam in heavy oil reservoir with the same net pay. For cyclic superheated steam simulation, the heating area gradually increases as superheated degree increases. The heating area of dry steam is slightly lower than superheated steam with a given superheated degree. While the superheated degree is over 20^{o}C, the heating zone basically increases no longer. It is the reason why the cumulative oil production slightly increases when superheated degree is over 20^{o}C that there is the almost same temperature and heating area in the same reservoir. The distribution of oil saturation is shown in Fig. 4. For the same mass of steam injection, the area of low oil saturation is larger after injecting superheated steam than injecting wet steam. The area of low oil saturation is slightly lower after injecting dry steam than injection superheated steam, as shown in Fig. 4. Therefore, for superheated steam, on the one hand the larger specific volume increases swept volume of steam injection, on the other hand, the stronger distillation effect increases oil displacement efficiency in reservoirs. The two aspects can greatly improve oil recovery efficiency of heavy oil reservoirs.

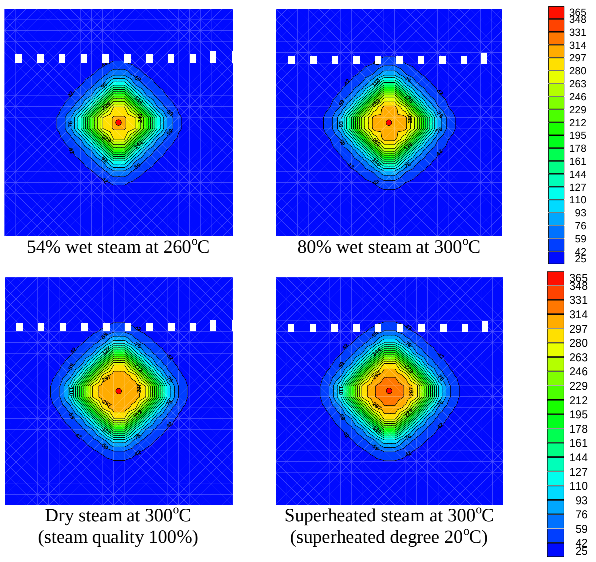


Figure 3. The temperature distribution for different steam in the same reservoir

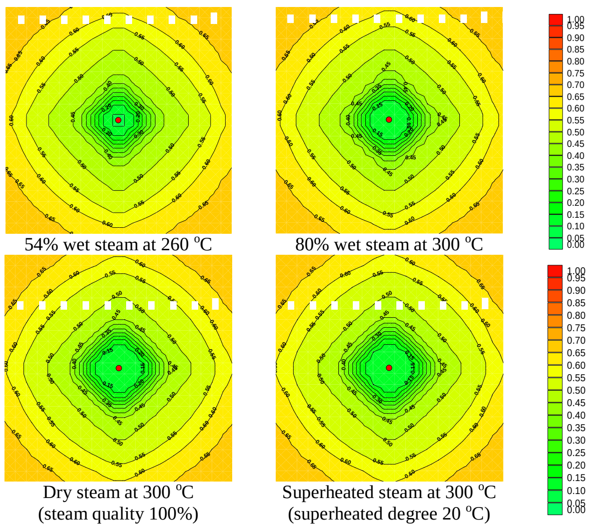


Figure 4. The distribution of oil saturation for different steam in the same reservoir

IV. Applications

Large-scale cyclic wet steam stimulation was carried out in GQ 3 zone of Henan Oilfield in February 2005. Until February 2010, the cumulative cycles of cyclic wet steam stimulation reached 261 in the zone. The cumulative mass of wet steam injection was 20.4464×10^4t. The cumulative oil production was 7.7742×10^4t. The water recovery percentage was 100.9%. The oil-steam ratio was 0.30. In August 2009, cyclic superheated steam stimulation was carried out in GQ 3 zone. It was divided into two types that were respectively the superheated steam injection after cyclic wet steam stimulation in the old layer and the direct cyclic superheated steam stimulation in a new oil layer. At present, the cumulative cycles of cyclic superheated steam stimulation have been up to 52. The cumulative cycles were 37 in the old oil layer. The cumulative cycles were 15 in the new oil layer. The cumulative mass of superheated steam was 3.3178×10^4t after cyclic wet steam stimulation in the old oil layer. The cumulative oil production was 1.2661×10^4t. Compared with the former cyclic wet steam stimulation, the oil-steam ratio was up to 0.35 from 0.30 and the water cut decreased to 69.52% from 82.12%, which showed that cyclic superheated steam stimulation obviously improved development effect of old oil layer. The development effect was better in the new layer than the old layer. The oil-steam ratio was up to 0.52 during cyclic superheated steam stimulation in the new layer. The results are tabulated in Table II.

TABLE II. The Comparison of Development Effect Between Wet Steam and Superheated Steam

Stage		Total number of cycles	Total well number	Cumulative steam injection ($\times10^4$t)	Cumulative oil production ($\times10^4$t)	Water cut (%)	Oil-steam ratio (t/t)
Wet steam stimulation		261	34	20.4464	7.7742	72.63	0.30
Superheated steam stimulation	Old layer	37	18	2.6276	0.9086	70.58	0.35
	New layer	15	11	0.6902	0.3575	66.44	0.52
	Total	52	29	3.3178	1.2661	69.52	0.38

V. Conclusions

The recovery mechanisms from superheated steam injection mainly include distillation effect of superheated steam, oil viscosity reduction due to high temperature, thermal expansion of heavy oil, larger sweep area and higher displacement efficiency of superheated steam.

The cumulative oil production of cyclic superheated steam stimulation is obviously higher than that of cyclic wet steam stimulation when the same mass of steam is injected into heavy oil reservoirs. The cumulative oil production gradually increases as superheated degree increases, but the incremental oil degree becomes low when superheated degree is over 20°C. For the same mass of steam, heating area and steam chamber are lager after injecting superheated steam than wet steam. Meanwhile, the distillation effect is stronger after superheated steam due to the higher temperature and the lower pressure resulting in more significant incremental oil production.

Under a condition of the same oil production, the steam consumption was lower after injecting superheated steam than wet steam in the same heavy oil reservoirs. Superheated steam can carried more heat and its specific volume is larger, which can effectively enlarge sweep volume and save large amount steam injection.

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