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Superiority of Superheated Steam Flooding in Development of High Water-cut Heavy Oil Reservoir

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Abstract. The dryness of superheated steam is 100% and it exists in the form of pure steam whose properties are like ideal gas. When the steam has a large degree of superheat, it may take a relatively long time to cool, during which time the steam is releasing very little energy and transmitted long distances. The heating radius of superheated steam in the formation is 5-10m larger than saturated steam. In the heating area of superheated steam, the comprehensive effects by superheated steam (crude oil viscosity reduction, improved flow environment, changes in rock wettability and improved oil displacement efficiency, etc.) is much higher than that of saturated steam. Superheated steam stimulation in Kenkyak high water cut heavy oil reservoir pilot test results showed that the average daily oil production of single well by superheated steam stimulation was 2-4 times than that of saturated steam stimulation. Superheated steam is more effective to heat water-invaded oil reservoir than saturated steam.

Introduction

As the depletion development time increases, the reservoir pressure decreases further and the oil production rate declines with the water-cut going up[1-3]. There are little or no economic benefits if continuing to develop by natural energy. Therefore, In order to solve the problems encountered during the process of development, a series of studies and pilot tests have been launched to improve the production performance and economic benefits. In Kenkiyak Pre-salt oil reservoir, recovery by natural energy, the daily production was only 1~2m^3/d, which was far from the economic margin. Later by saturated steam flooding, the average daily production increased to 3m^3/d, which was still not good enough. Several pilot tests of conventional techniques applied in different blocks but did not get expected results. Hot water, polymer and saturated steam flooding only played a role of supplying reservoir energy, and did not increase oil production obviously. Conventional thermal recovery is not suitable for this kind of reservoir. Therefore, the technical challenge encountered after many years of depletion development. In order to develop a reasonable effective technology for high water-cut viscous reservoir, valuable experience and knowledge was obtained from pilot tests of conventional thermal recovery. Saturated steam flooding did not effectively increased oil production. Main reasons are following: Strong water invasion for many years as the reservoir had huge aquifers. The quantity of heat carried by saturated steam is limited to increase the reservoir temperature high enough[4]. If the temperature of saturated steam is increased, the pressure is also increased[5]. But the maximum pressure is controlled by steam boiler and burst pressure of the reservoir rock. If increasing the temperature of saturated steam, the pressure keeping unchanged or changed a little. Then superheated steam is gotten[6], which has a higher temperature, carries more heat and has greater heating capacity than saturated steam.

Numerical Simulation of superheated steam flooding Process

Modeling in new methods A three dimensional simulation model was built using CMG STARS and was tuned with experimental data from the well 43. The model consisted of a vertical matrix block divided into 24 grids in Z direction, 15 grids block in X direction, and 15 grids block in Y direction.

Total matrix block length was 13.3m with 0.808m of width and depth in X and Z directions. The single-well model is homogenous and the parameters are summarized in Table 2. Dead-oil viscosity versus temperature and the relative permeability curves follow in Table 3 and figure 1 respectively. History matching of oil production from a single well was first conducted according to actual production of well 43. Sensitivity of the results to input values of the temperature and superheated degree of superheated steam, the scope of formation heated by superheated steam were studied and also parameters such as cumulative oil produced, amount of oil produced were investigated. And also saturated steam flooding process were investigated and compared with the results of superheated steam flooding on the base of the same single-well model[7]. The well 43 went through in sequence all the three production stages such as by natural depletion, by saturated steam flooding, and by superheated steam flooding. The injection of superheated steam and saturated steam were under the same pressure but the temperatures were different, what were chosen so as to resemble average field injection conditions. For the first cycle 2600t of steam is injected. The superheated steam injection rate was 150t/d.

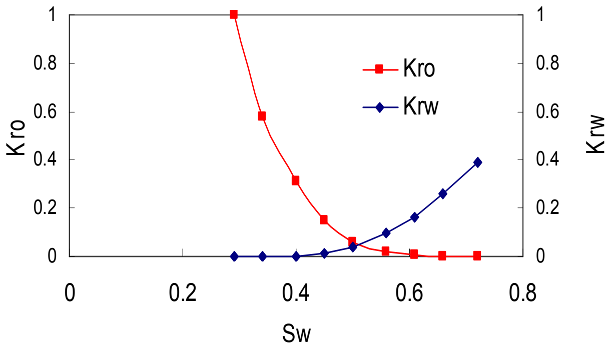


Fig.1 Relative permeability of oil and water l

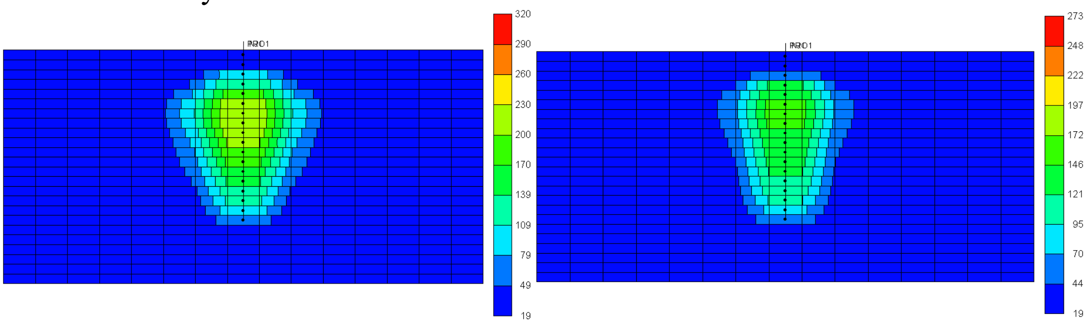
Table2 Parameters for the single-well mode

Reservoir depth	280m
Initial reservoir pressure	2.82MPa
Net Pay	17m
Porosity	36.60%
Permeability	1875md
Oil saturation	65%
Dead oil viscosity	269cp

Table3 Dead-oil viscosity versus temperature

Temperature℃	20	30	50	80	150	200
oil viscosity(mpa.s)	262	134	44	14	3.6	2.2

Results from model calculation Figure 2 shows the temperature distribution and shape of the steam chamber as degree of superheat is varied between 10°C and 70°C as well as superheated steam temperature between 260°C and 320°C under the same pressure. Figure4 demonstrates an important dependence on degree of superheat in that the greater degree of superheat case has greater steam override. The heated volume is larger at greater degree of superheat. Obviously, the scope of steam chamber is controlled by steam override.



(a) Superheated steam flooding (b) saturated steam flooding

Fig.2 Temperature distribution and shape of the steam chamber

Table 4 summarized the various total rates of injection for the well 43 as well as the oil production and OSR. The down-hole steam temperature and degree of superheat were fixed at 300°C and 50°C respectively for all cases. The changes in cumulative production and OSR were significant. It is clear that as the rate decrease, the OSR increases, On the other hand, as the superheated steam injection rate increases the oil production reaches a peak and then declines markedly, Over injection does not aid recovery. There exists a reasonable injection strength that is 150t/m.

Figure 3 shows oil rate and cumulative oil production for superheated steam and saturated steam flooding under the condition of the same injection rate and total injection. Superheated steam flooding results in significantly greater production. The mean initial daily production increased from 5 m3/d by saturated steam flooding to 15 m3/d. After roughly 800 days of producing, superheated steam flooding produced about 150% more oil than that of saturated steam. In the superheated steam flooding case, the cumulative oil production is 4940t and the OSR is 1.8 at 800 days. The cumulative oil production is 2930t greater than that of saturated steam due to extra oil production associated with the injection of superheated steam, which revivified the marginal field.

Table 4 Various total rates of injection for the well 43 as well as the oil production and OSR

steam injection rate \t/d	total injection \m^3	durations \d	cumulative production \m^3	OSR \m^3/m^3
80	1200	800	2414.4	2.01
100	1500	800	2851.5	1.90
130	1950	800	3420.3	1.75
150	2250	800	3782.3	1.68
180	2700	800	4077.0	1.51

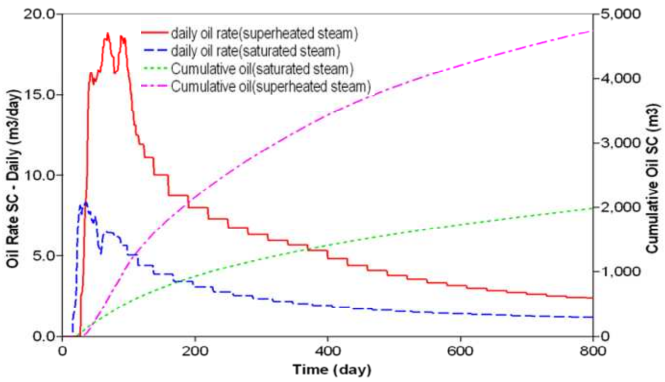


Fig.3. Oil rate and cumulative oil production for superheated steam and saturated steam flooding

Heavy oil superheated steam flooding production features in high water-cut reservoirs

Production performance of superheated steam flooding Pilot tests performed covered the saturated steam flooding in 28 wells and the superheated steam flooding in total 80 wells. The Superheated steam is more effective than the saturated one in heating water-invaded oil reservoirs. Among all the pilot test wells, 13 went through in sequence all the three production stages, i.e. by natural energy, by saturated steam flooding, and by superheated steam flooding. First by natural energy, the daily production was only 1~2m^3/d, which is far from economic limit. Later by saturated steam flooding, the average daily production increased to 3m^3/d, which was still not ideal. Two years later by superheated steam flooding, the mean daily production was raised to 8~9m^3/d (Fig2.), which increased the daily oil production greatly. The production period with superheated steam flooding has lasted over 800 days in the first cycle, and still extending ahead. With high initial daily oil production by superheated steam flooding, the average increase of oil was 6.4t/d, which was 2.8t/d higher than the saturated steam .Cyclical oil production reached 5160t by superheated steam flooding, which was 3230t more than saturated steam stimulation. Cyclical oil-steam ratio was 1.8 by superheated steam flooding, 0.7 higher than that of saturated steam (Fig.4).

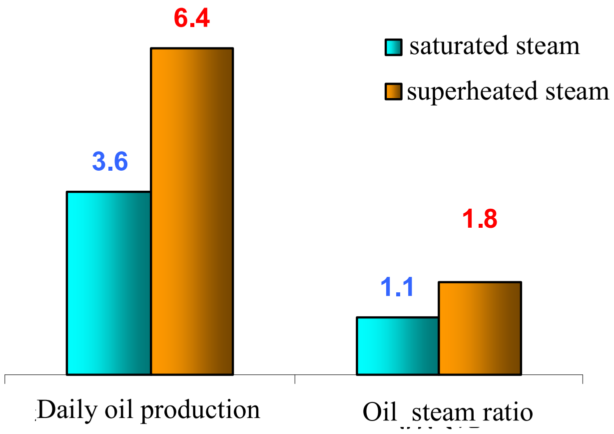


Fig.4. Comparisons of mean daily oil production increment and OSR

Evaluation of superheated steam flooding test results The temperature and degree of superheat profiles in temperature observational wells and injectors as well as the fluid temperature at the wellhead of producers in the test area are the major data for monitoring the changes in reservoir temperature distribution[8]. Converted to superheated steam flooding, the formation temperature kept rising and the middle and upper parts of the formation were heated with the maximum temperature reaching 220°C in the inter-well formation. Horizontally, the formation with the temperature of more than 150°C covers a length of 50~60m and the steam swept radius is about 30m.

Conclusions

The reservoir conditions of Pre-salt oil field are suitable for superheated steam flooding development after long time production by depletion. This study suggests that the region immediately around wells is heated effectively, but that temperature has not penetrated the formation to a great extent. Accordingly, the remaining oil saturation is distributed between wells and generally low in the formation due to gravity override of superheated steam. Superheated steam will last longer time than saturated steam under reservoir conditions and heat larger scope of formation. Superheated steam is more effective to heat water-invaded oil reservoir than saturated steam.

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