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Superheated Steam Huff and Puff to Revivify a Marginal Pre-salt Heavy Oil Reservoir

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Abstract

The Kenkiyak pre-salt oil field is a heavy oil reservoir with the average porosity of 36.6%, the average permeability around $1875 \times 10^{-3} \mu m^2$, the buried depth between 290~380 m, the dead oil viscosity within 144~691mPa.s @20^oC, the reservoir temperatures between 18.8~20^oC. From 1967 to 2002, the reservoir was developed by depletion. As a result, the average reservoir pressure has dropped from 5.9Mpa to 1.8 MPa. The serious heterogeneous characteristics and rapid water invasion made the water-cut of wells as high as 76%. Furthermore, the average well production rate declined from the original 8 m^3/d to the later 1~2m^3/d., and was staying at this level for a long time. The field was hovering at the economical margin in 2002. In 2003, the operator launched a series of studies and pilot tests to improve the production performance and economic benefits. But there is no proven current recovery technique that can be economically applicable to such viscous oil reservoirs. However, there are huge amount of hydrocarbon accumulation in such reservoirs that can only be exploited with new concepts. Superheated steam huff and puff as a superior technology for the recovery of high water-cut heavy oil reservoirs has been pilot tested in Pre-salt oil reservoir and has found satisfactory development results. This work introduces this new recovery technique of superheated steam huff and puff to effectively develop serious water-invaded heavy-oil reservoirs, and reviews the main practices we have performed, including simulation studies, pilot tests, challenges encountered and solutions, and current effects. Valuable knowledge and experiences have been obtained in terms of superheated steam huff and puff in such reservoirs after many years depletion development, providing reliable operational experience and technical support for Kenkiyak pre-salt reservoir and similar oilfields.

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 huff and puff, 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 huff and puff 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[4-7]. If the temperature of saturated steam is increased, the pressure is also increased[8-12]. 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[13-17], which has a higher temperature, carries more heat and has greater heating capacity than saturated steam. Superheated steam is the steam that is superheated by the number of temperature degrees through which it has been heated above its saturation temperature[2-4]. The difference between superheated steam and saturated steam is called degree of superheat[5-7]. With superheated steam there is no direct relationship between temperature and pressure[18-22]. Therefore at a particular pressure it may be possible for superheated steam to exist at a wide range of temperatures[2-5]. This is a useful increase in energy[23-25]. 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[26-29]. Superheated steam has to cool to give up heat, whilst saturated steam changes phase[30-31]. Superheated steam is more effective to heat water-invaded oil reservoir than saturated steam. In order to evaluate quantitatively the production performances by using the new method, numerical simulation technique was employed to find out the advantages of superheated steam huff and puff in high water-cut heavy oil reservoir.

Reservoir geological situations of Pre-salt oil field

The Pre-salt oil field is situated on the top of salt dome of the Kenkiyak district. The target formation is the Middle Jurassic formation. The reservoir is mainly made up of medium to fine sandstones, and silt fine sandstones with 6.54% clay minerals. The reservoir rocks are unconsolidated, being mainly porous cement. The Middle Jurassic formation is divided into two sub groups, J-I and J-II, which have the same oil/water contact with the depth of -380m. The oil/water relationship is simple with the upper part of the structure being the pure oil zone and the lower part water zone. The oil layers are well separated, providing favorable conditions for separate layer development.

The burial depth of the Middle Jurassic formation ranges from -290 to -380m. The oil formation is thick with the average effective thickness of 17.03m and the average net /gross thickness ratio is over 0.70.

The Middle Jurassic formation is a typical shallow, medium to massive laminated structural lithologic conventional heavy oil reservoir with edge water and high porosity, high permeability. The average porosity and permeability are 32.5% and $1875 \times 10^{-3} \mu m^2$ respectively.

Table1 show the reservoir parameters and Fluid properties of the Middle Jurassic formation in Pre-salt oil reservoir.

Table1 Reservoir parameters and Fluid properties of the Middle Jurassic formation

Average effective thickness m	OOIP 104t	Porosity %	Perm. 10-3m2	Original oil saturation %	Dead oil viscosity mPa.s @50°C	Oil density (20°C) g/cm3	Formation temperature °C	Original formation pressure MPa
17	54	21-38	2.62-8840	65	144-691	0.9053	18.8	2.82

The oil properties are as follows: (l) the oil density is 0.987g/cm, at 20^{o}C, (2) the oil viscosity is 144-691mPa.s at 20^{o}C, (3) the resin and asphaltene content is about 33.3%, (4) the wax content is 2.2%. According to the heavy-oil classification system in China, it is ordinary heavy oil.

Pre-salt oil field has been produced using cyclic saturated steam injection since 1983 and been shifted to saturated steam flooding in main part of reservoirs between 1984 and 1996. The original well spacing has reduced from 14lm to 100m between 1984 and 1997. In some areas, well spacing is now 70m. At the end of 2009, the cumulative oil recovery was 14.3% of the OOIP.

Numerical Simulation of superheated steam huff and puff Process

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 huff and puff process were investigated and compared with the results of superheated steam huff and puff on the base of the same single-well model. The well 43 went through in sequence all the three production stages such as by natural depletion, by saturated steam huff and puff, and by superheated steam huff and puff. 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.

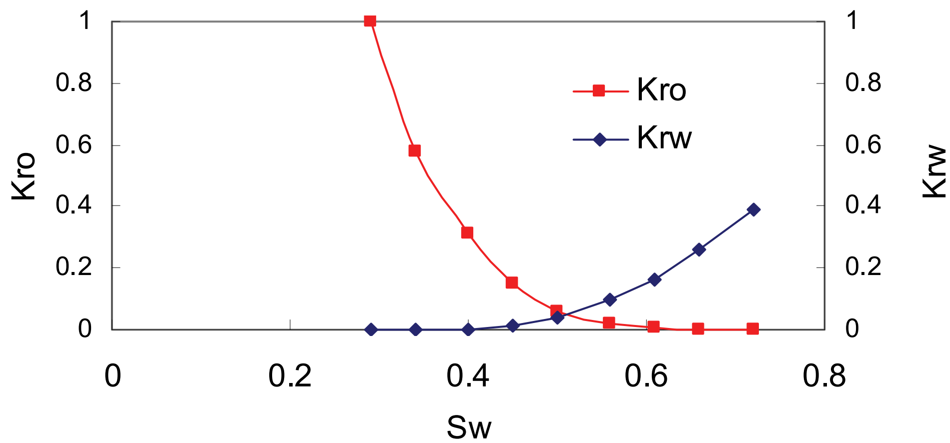


Fig.1 Relative permeability of oil and water

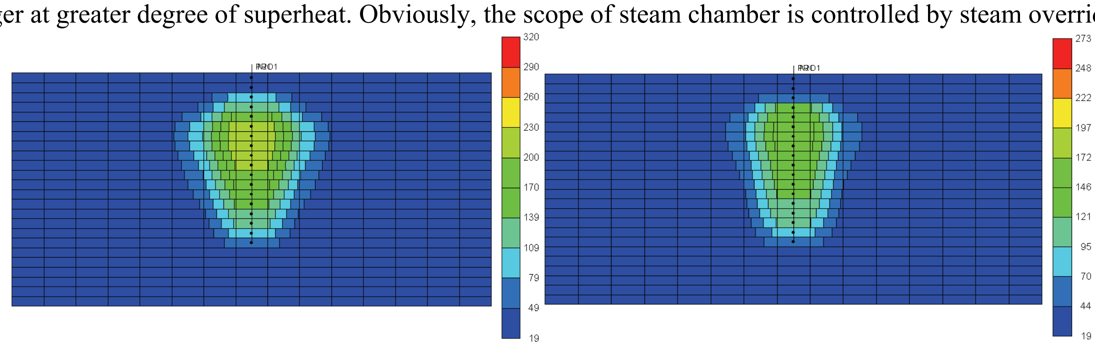
Table2 Parameters for the single-well model

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

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 huff and puff **(b) saturated steam huff and puff**

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.

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 \m3	durations \d	cumulative production \m3	OSR \m3/m3
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

Figure 3 shows oil rate and cumulative oil production for superheated steam and saturated steam huff and puff under the condition of the same injection rate and total injection. Superheated steam huff and puff results in significantly greater production. The mean initial daily production increased from 5 m^3/d by saturated steam huff and puff to 15 m^3/d. After roughly 800 days of producing, superheated steam huff and puff produced about 150% more oil than that of saturated steam. In the superheated steam huff and puff 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.

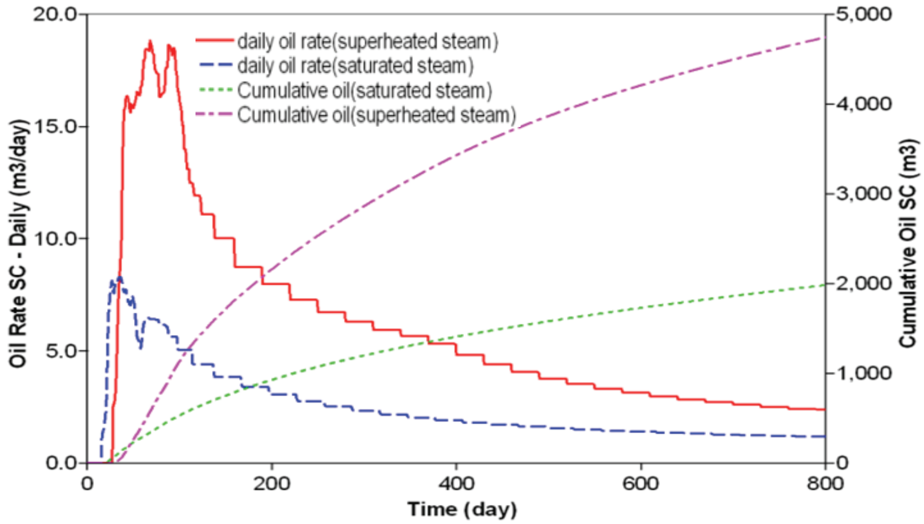
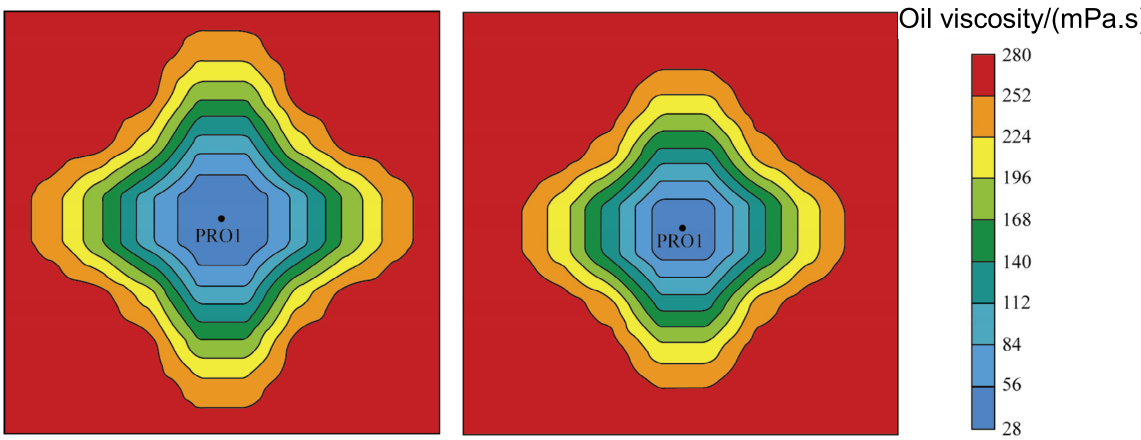


Fig.3. Oil rate and cumulative oil production for superheated steam and saturated steam huff and puff

Figure 4 plots the oil viscosity at the end of cyclic superheated steam and saturated steam injection operations respectively. From these plots, the reservoir volumes with the lowest oil viscosity are close to wells. The oil viscosity of the entire reservoir volume has not been increased systematically and the distribution of heat is concentrated around wells. But the scope heated by superheated steam is larger than that of saturated steam and the oil viscosity decreased more greatly within the scope. Oil in the heated area can flow into well bores more easily and more quickly.



(a) superheated steam huff and puff (b) saturated steam huff and puff

Figure4. The distribution of oil viscosity after the same tons of steam injection in one cycle

Heavy oil superheated steam huff and puff production features in high water-cut reservoirs

Brief introduction to the superheated steam huff and puff pilot test

The pilot area of Pre-salt oil field was put into saturated steam huff and puff development with 28 wells from 2003. In Oct.2005, superheated steam pilot tests were started in well 43, and the tests were expanded to another 52 wells between 2006 and 2009. Among the entire pilot test wells, 13 went through in sequence both the two tests that by saturated steam huff and puff and by superheated steam huff and puff. Right now, the whole block is being put into superheated steam huff and puff development.

The steam drive pilot tests were targeted at J-II of Middle Jurassic formation with the burial depth of -320m. The formation has good communication and uniform vertical reservoir properties. Before the tests, natural depletion had been produced for 40 years and some wells went through saturated steam huff and puff. The production rate of a single well declined averagely from the original 8 m^3/d to the later 1~2m^3/d. Before converting to superheated steam huff and puff, some wells had the average residual oil saturation of 0.60 and the average formation pressure of 1.8Mpa and the recovery factor of 11% in the tested block.

The expanded superheated steam huff and puff wells were situated in the remaining wells and the vertical target zone remained the same, i.e. Fig.5. The reservoir conditions were generally similar to those in the pilot area.

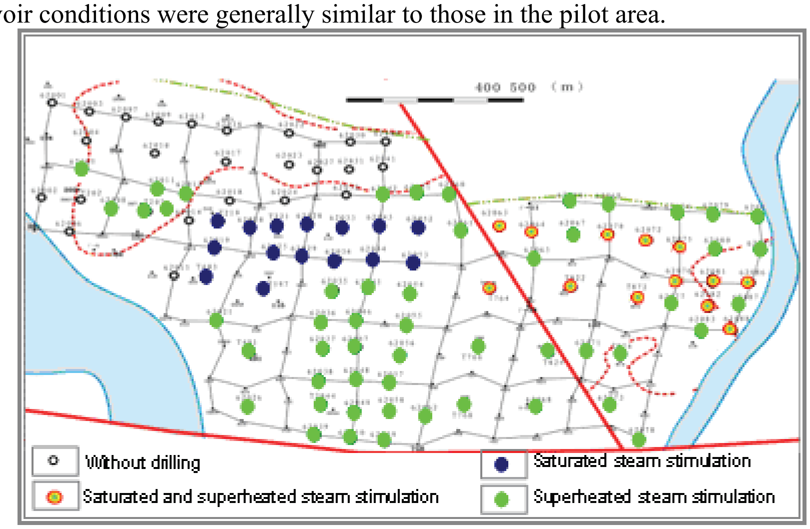


Fig.5. Well Locations of steam flood pilot tests

Production performance of superheated steam huff and puff

Pilot tests performed covered the saturated steam huff and puff in 28 wells and the superheated steam huff and puff 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 huff and puff, and by superheated steam huff and puff. First by natural energy, the daily production was only 1~2m^3/d, which is far from economic limit. Later by saturated steam huff and puff, the average daily production increased to 3m^3/d, which was still not ideal. Two years later by superheated steam huff and puff, the mean daily production was raised to 8~9m^3/d (Fig.6), which increased the daily oil production greatly. The production period with superheated steam huff and puff has lasted over 800 days in the first cycle, and still extending ahead. With high initial daily oil production by superheated steam huff and puff, 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 huff and puff, which was 3230t more than saturated steam stimulation. Cyclical oil-steam ratio was 1.8 by superheated steam huff and puff, 0.7 higher than that of saturated steam (fig.7).

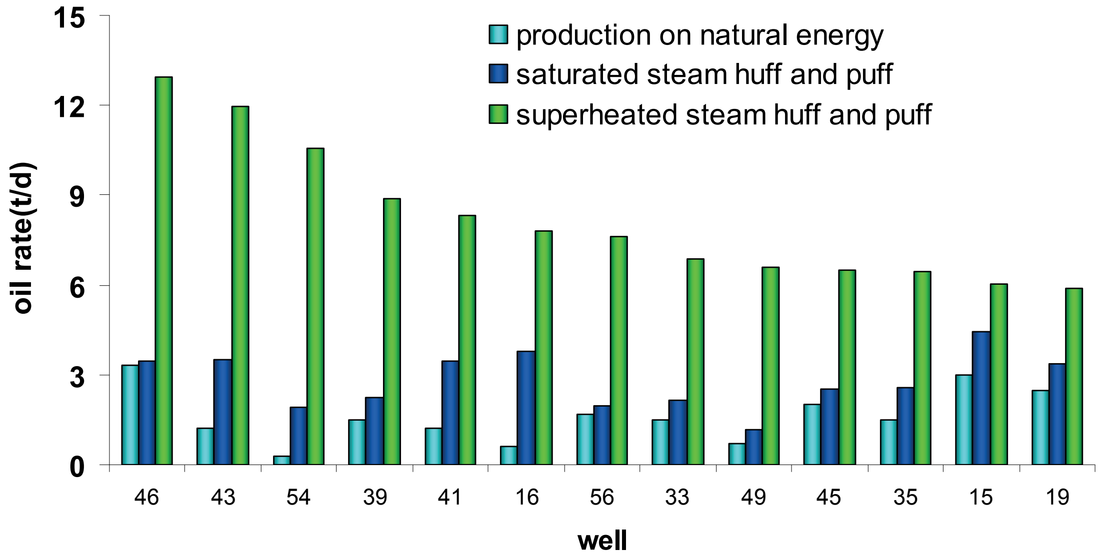


Fig.6. Oil rate of single well under three different recovery methods

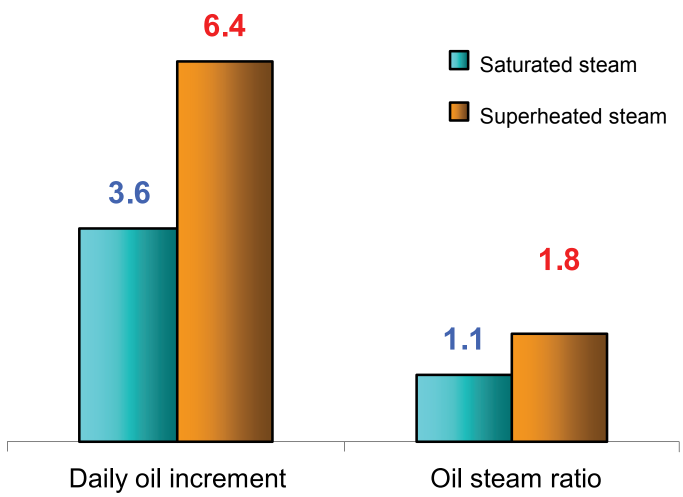


Fig.7. Comparisons of mean daily oil production increment and OSR

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 (table 5.).

Converted to superheated steam huff and puff, 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.

Table5 temperature and degree of superheat versus depth

Depth	Pressure	Temperature	Degree of superheat
(m)	(MPa)	(℃)	(℃).
0	2.61	273.2	44.8
50	2.59	272	44.1
100	2.57	270.9	43.3
150	2.55	269.7	42.5
200	2.53	268.6	41.8
250	2.52	267.5	41
290	2.5	266.6	40.5
292	2.5	266.4	40.3

Evaluation of superheated steam huff and puff test results

In the pilot superheated steam huff and puff tests (5years), total steam injection has reached 13.3×10^4t, oil production 23.9×10^4t, oil/steam ratio 1.8, oil production rate 7.2% and recovery 33.53%. Compared with the estimated oil production with saturated steam huff and puff, the incremental oil production has been 15.4×10^4t and recovery has been improved by 5.84%. Based on the program design, the pilot tests have achieved satisfactory development results.

Supporting techniques for superheated steam huff and puff

Problems encountered during the tests

Superheated steam has seldom been reported to be used to drive heavy oil before due to the limitation of boiler's properties[32-33]. However, through two years of research, we developed an innovative model of boiler that can successfully overcome the challenges caused by boiler's properties (Fig.8). The so-called superheated steam is to heat the saturated steam under a certain pressure until it has been converted to the dry steam from a wet one.

The wet steam(dryness factor ≤50%) must be passed through an additional heat exchanger to improve its quality (dryness factor ≥90%) , then went through steam-water separators to detach water phase . The detached dry saturated steam was superheated went through a second heat exchange stage in a separate superheater unit of the boiler.

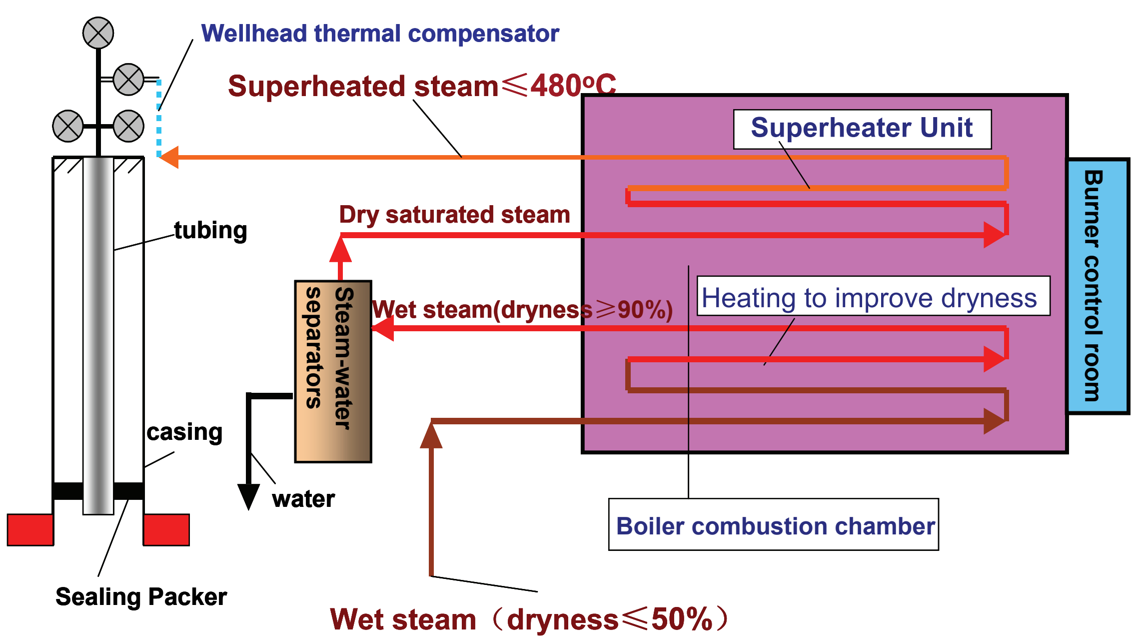


Fig.8 Superheated steam generating process

The wells in the test area are in poor condition. When steam flood became effective, the bottom-hole temperature in the producers increased gradually and some of the wells had sanding problems, resulting in casing damage to different degrees in many wells and affecting fluid production and other operations as well as data collecting.
During superheated steam injection, the produced fluid was high in temperature and volume with fast changing water cut and unstable sand production, making the conventional thermal production oil pumps hard to meet the requirements of fluid lifting, sand control and high temperature resistance and corrosion proof in superheated steam stimulation. The oil pumps had low pump efficiency and serious leakage problems, leading to short pump checking periods and heavy workload of pump checking in the course of high sand production during the early days after superheated steam huff and puff.
Temperature gradients over the heat transfer surface may occur with superheated steam to damage steam injection pipe string[33-34]. In the pilot tests, nitrogen had to be supplied periodically into the annulus in injectors so that decrease temperature gradients, and ensured the bottom-hole steam quality could be at about 100% and the degree of superheat was high about 50^oC as required by the design.
The high temperature and degree of superheat testing techniques are to be perfected urgently to ensure the gathering of monitoring data of the system.
The expanded test area is not controlled sufficiently and the vertical steam absorption conditions should be improved urgently.

Conclusions and recommendations

There is no direct relationship between temperature and pressure with superheated steam. At a particular pressure it can exist at a wide range of temperatures for superheated steam, which is a useful way to increase steam energy. 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. Superheated steam has to give up heat during becoming cool, whilst saturated steam changes phase. Therefore, 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.
The reservoir conditions of Pre-salt oil field are suitable for superheated steam huff and puff 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.
The major injection and production technologies developed for the oil superheated steam huff and puff in Pre-salt oil field are mature and advanced, having solved the problems of high temperature lifting and high temperature long term superheated steam injection. The supporting techniques such as high temperature dynamic monitoring and separate layer steam flood have solved many of the problems encountered during steam flood, providing technical support for the commercialization of steam flood.
Follow-up study of the tests, strengthening the collecting of monitoring data and timely adjusting the programs are necessary for ensuring the success of superheated steam huff and puff.
It is recommended to track the expanded tests more closely to provide experience for commercialization and continue the research of the supporting techniques to provide technical support for commercialization.

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