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New Findings on Heatloss of Superheated Steam Transmitted Along the Wellbore and Heating Enhancement in Heavy Oil Reservoirs

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Abstract

At the conclusion of several cycles conventional saturated steam huff and puff in heavy oil reservoirs, the heating radius are typically only 20-30m as it went through successive saturated steam huff and puff. The heating scope can’t be enlarged by continuing saturated steam huff and puff any more. However, superheated steam huff and puff as a additional heavy oil recovery significantly increased heating radius of saturated steam huff and puff. Conventional saturated steam huff and puff theory is not applicable for superheated steam. In this study, superheat steam heat transmission mathematical models was established by three laws such as the law of conservation of mass, the theorem of momentum and the law of conservation of energy , thermodynamics and fluid flow theories. Based on models, the parameters such as temperature, dryness, pressure, degree of superheat, heat loss along the wellbore were calculated. This work analysis the superior properties of superheated steam and bring forward superiority of superheated steam huff and puff to effectively develop heavy oil reservoirs in recovery mechanisms, including simulation studies, and current pilot test effects.

Introduction

After several cycles saturated steam huff and puff in heavy oil reservoirs, the heating radius are typically only 20-30m, the maximal radius in perfect reservoir is about 50m[1-3]. In the ultra-heavy oil reservoir, oil saturation stay in original state out of the heating radius as it went through successive saturated steam huff and puff . The heating scope can’t be enlarged by continuing saturated steam huff and puff any more due to the limited heat carried by saturated steam and the serious heatloss during its transmission. In conventional heavy oil reservoirs, oil has a certain capacity of flowing in the original formation. When the reservoirs went through stages by depletion or some cycles saturated steam huff and puff, the reservoir pressure dropped quickly and formation water was accelerated to invade in oil reservoir because of high oil and water mobility ratio. Water-cut increased rapidly and oil production decreased sharply after water went through bottom hole. The production performance was becoming worse and worse without changing development methods. These reservoirs were inappropriate for continuing saturated steam huff and puff and their properties probably hardly meet the criteria of saturated steam drive.There are huge amount of hydrocarbon accumulation in such reservoirs that can only be exploited with new concepts. The secondary enhanced oil recovery technology should be considered to improve oil production [3-4]. Whether the saturated steam superheated by the number of temperature degrees above saturation temperature would be as a new technology for the recovery of these heavy oil reservoirs. This work analysis the superior properties of superheated steam and bring forward superiority of superheated steam huff and puff to effectively develop these marginal heavy oil reservoirs in recovery mechanisms, including simulation studies, and current pilot test effects.

Heat transfer characteristics of superheated steam

The intensity of steam heat transfer in the wellbore and formation is usually measured by heat transfer coefficient in thermodynamics. The physical meaning of heat transfer coefficient is the unit heat pass through the unit heat transfer area in the per unit time under $1^{\circ}C$ temperature difference[7]. Obviously, the greater the heat transfer coefficient, the more the heat transfer per unit time. For the steam carried a certain quantity of heat, the smaller the heat transfer coefficient, the less heat flow in the unit time, the longer the heat transfer duration. Table 1 lists the heat transfer coefficients of different fluids in heat transfer, which indicates that, when there is phase change of fiuids during the process of heat flowing will lead to greater heat transfer coefficients, and no phase change of fluids in heat flowing has smaller heat transfer coefficient, gas has the smallest. Figure3 demonstrates that superheated steam exists in the region above saturation line (Dryness x=1) and belongs to 100% degree of dry gas. The trend of isotherms in Fig.3 shows the higher the degree of superheat is, and the superheated steam is more close to ideal gas[10], also the heat transfer coefficient is smaller. The calculation from Table 2 is that the heat transfer coefficient is approximately equal to that of air and is only 1/150-1/250 as much as saturated steam. In addition, superheated steam has no phase change in heat transfer and the heat transfer coefficient is low .But for saturated steam, the loss of heat will cause some of the steam to condense and the phase changes occur , heat transfer coefficient is larger. As is shown from Table 2. According to Newton's law of cooling (Formula 1), the heat flow rate depends on the heat transfer coefficient, heat transfer area and the temperature difference. In the same heat transfer area, the temperature difference of superheated steam is greater than the temperature difference of saturated steam, but the heat transfer coefficient for superheated always is much lower than that for saturated steam, the temperature difference is relatively much less than heat transfer coefficient difference. The higher the degree of superheat, the lower the heat flow rate , Formula 2 shows that, in passing along the same heat transfer area, the heat transfer rate ratio between superheated steam and saturated steam is probably equal to the heat transfer coefficient ratio, That is 1/150-1/250. Superheated steam carries more heat than saturated steam, and superheated steam heat loss rate is less than that for saturated steam[11]. It can take a relatively long time to cool, during which time the steam is releasing very little energy and transmitted long distances, which is useful increase in heating scope. Superheated steam can overcome the limitation that after 10 cycles of saturated steam stimulation, the maximum heating radius is not enlarged .

$$Q = \alpha A(T - T_w) \tag{1}$$

$$\frac{Q_{\mathrm{sup}}}{Q_{\mathrm{s}}} = \frac{\alpha_{\mathrm{sup}} A(T_{\mathrm{sup}} - T_{\mathrm{w}})}{\alpha_{\mathrm{s}} A(T_{\mathrm{s}} - T_{\mathrm{w}})} = \frac{\alpha_{\mathrm{sup}}}{\alpha_{\mathrm{s}}} \cdot \frac{(T_{\mathrm{s}} + T_{\Delta} - T_{\mathrm{w}})}{(T_{\mathrm{s}} - T_{\mathrm{w}})} = \frac{\alpha_{\mathrm{sup}}}{\alpha_{\mathrm{s}}}(1 + \frac{T_{\Delta}}{T_{\mathrm{s}} - T_{\mathrm{w}}}) \approx \frac{\alpha_{\mathrm{sup}}}{\alpha_{s}} \tag{2}$$

Table 1 The value of heat transfer coefficient

Heat transfer condition	‘α’ value/ W/(m^2·K)	‘α’ common use value /W/(m^2·K)
Saturated steam heated or condensed	5000～15000	10000
Water boiling	1000～30000	3000～5000
Water heated or cooling	200～5000	400～1000
Oil heated or cooling	50～1000	200～500
Superheated steam heated or cooling	20～100	
Air heated or cooling	5～60	20～30

Synthetic Evaluating Model for superheated steam injection down the wellbore

Assumptions of the model foundation are following: (1)Superheated steam flow is a constant mass flow in the wellbore; (2) The bottom of insulated tubing is sealed with packer setting to ensure no steam into annulus filled with air. (3) The superheated steam flow in the wellbore is one dimensional steady flow. During superheated steam flow pressure and temperature in the same cross section are equal everywhere; (4) Heat transfer from inner surface of the tubing to the outer ring of the cement is steady but from outer ring of cement to formation the heat transfer is not steady, and the model is built without considering the heat transfer in longitudinal direction along the wellbore. The wellbore structure is shown in Figure1.

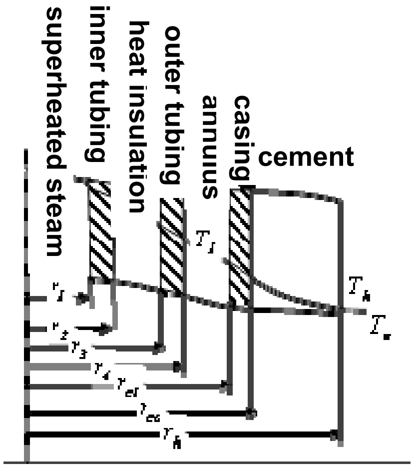


Fig.1 wellbore structure

The mathematical model is founded on the base of three laws：(1)The law of conservation of mass (2)The theorem of momentum (3)The law of conservation of energy.Equations used in the calculation are as follows:

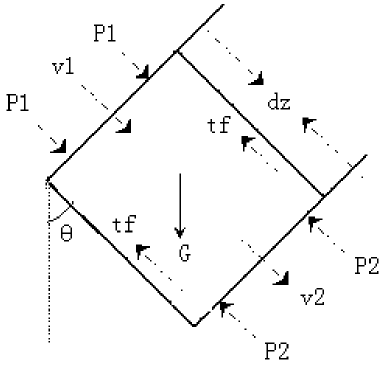


Figure 2 Mechanical analysis of micro element

1)Mass Conservation Equation

Superheated steam injection process is constant mass flow and the mass conservation equation is

$$\rho_1 v_1 A = \rho_2 v_2 A = i_s \qquad (3)$$

2) Theorem of Momentum Equation

$$dpA = \rho_m A dzg\cos\theta - \tau_f + \rho_1 v_1^2 A - \rho_2 v_2^2 A \qquad (4)$$

Equation 4 described superheated steam pressure drop along the wellbore on the base of analysis of infinitesimal with taking into account the gravity impulse, and $\rho_m Adzg\cos\theta dt$ is gravity impulse within the dt time. The new equation of pressure drop dp was founded by the Theorem of Momentum.

3) Energy Conservation Equation

Considering frictional energy loss in the superheated steam flow, the superheated steam energy equation was established under the principle of conservation of energy:

$$\frac{dQ}{dz} + \frac{dW}{dz} = -i_s\frac{dh_m}{dz} - i_s\frac{d}{dz}\left(\frac{\upsilon^2}{2}\right) + i_s g\cos\theta \qquad (3)$$

The physical meanings of Equation 3 is that the internal energy change of micro element such as Figure 2 in unit time as well as the change of mechanical energy is equal to the heat transferred to the wellbore and friction loss.

Equation 3 not only considers the micro body of superheated steam mechanical energy change and the change of their own internal energy and water vapor to the transfer of heat, but also considers the steam flow process friction loss of energy dW, can be used to find out the superheated steam temperature change dT new equation.

4)Auxiliary equation

$$\frac{dh_m}{dz} = (\frac{\partial h_m}{\partial T})_p \frac{dT}{dz} + (\frac{dh_m}{dp})_T \frac{dp}{dz} \qquad (4)$$

The equation above can be translated into：

$$\frac{dh_m}{dz} = C_p \frac{dT}{dz} + \{\mathrm{V} - \mathrm{T}(\frac{\partial \mathrm{V}}{\partial \mathrm{T}})_{\mathrm{p}}\} \frac{dp}{dz} \qquad (5)$$

This equation is applicable to the all of solid, liquid and gaseous.

5）**Function relationship between saturated steam pressure and temperature**

$$t_s = 210.2376 p_s^{0.21} - 30 \qquad (6)$$

This equation can determine superheat degree of steam.

The mathematical model about superheated steam parameters distribution along the wellbore was established through the Equation1-6 .

Basic parameter selection

The parameters such as steam pressure, temperature and dryness distribution along the wellbore can be calculated by this mathematical model. In order to compare with saturated steam, the state parameters of superheated steam and saturated steam are shown in Table 2. The thermal enthalpy of superheated steam injected into wellhead is 24.81% more than that of saturated steam with dryness of 75% from the table.

Table 2 Parameters of differnt steam injection

Steam type	Pressure（MPa）	Temperature(°C)	Dryness(%)	Superheat degree(°C)	Injection rate(t/h)	Enthalpy(kJ/kg)
Superheated steam	4.00	300	100	49.4	8.00	2962.0
Saturated steam	4.00	250.6	75	0	8.00	2373.25

As the steam boiler is near the wellhead, the length of superheated steam flow on the ground surface is very short and is treated as part of wellbore . Reference base data for ground pipelines and shaft as shown in table 3

Table 3 Parameters of wellbore structure

Wellbore structure parameters	values	Wellbore structure parameters	Value
Inner tubing radius(m)	0.038	Outer tubing radius(m)	0.04445
thermal conductivity of heat insulation tube (W/(m.°C))	0.07	surface roughness of tubing (m)	0.0000457
Inner casing radius(m)	0.0807	Temperature gradient of formation(°C/m)	0.029
Outer casing radius(m)	0.0889	Thermal Conductivity of formation (W /(m·°C))	1.73
Blackness of inner casing surface	1.0	Thermal Conductivity of cement(W /(m·°C))	0.933
Outer cement radius(m)	0.213	Coefficient of temperature conductivity of formation (m^2/h)	0.00037
Ground temperature(°C)	21		

Comparison of different steam type

The state parameters of superheated steam and saturated steam on the wellhead are from Table 2, and the state parameters for the both superheated steam and saturated steam in the bottom well are shown in Table 4, the steam temperature, pressure, dryness distribution along the wellbore are shown in Figure 3 and Figure 4 and Figure 5.

Table 4 State parameters of superheated steam and saturated steam in the bottom well

Steam type	pressure （MPa）	temperature (°C)	dryness (%)	Superheat degree (°C)	enthalpy (kJ/kg)	heatloss （kJ/kg）
Superheated steam	3.56	273.97	100	28.8	2896.8	66.15
Saturated steam	3.77	247.04	64.06	0	2181.6	191.68

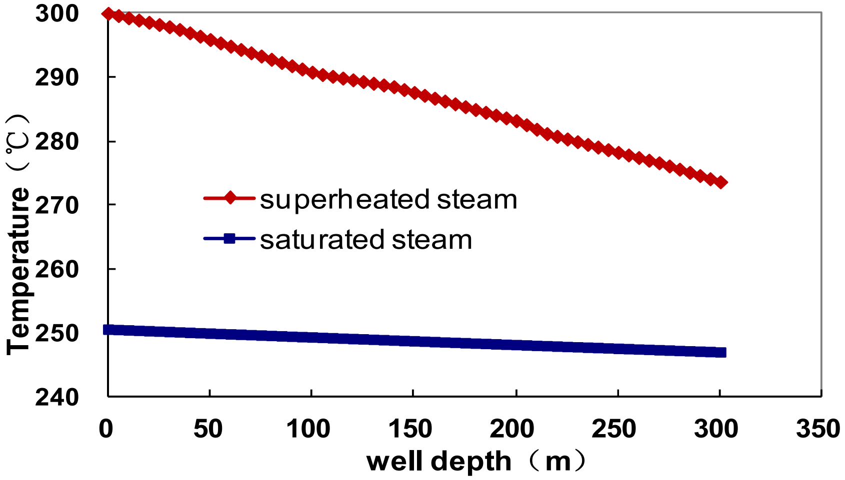


Fig.3 Comparison of temperature distribution along the wellbore

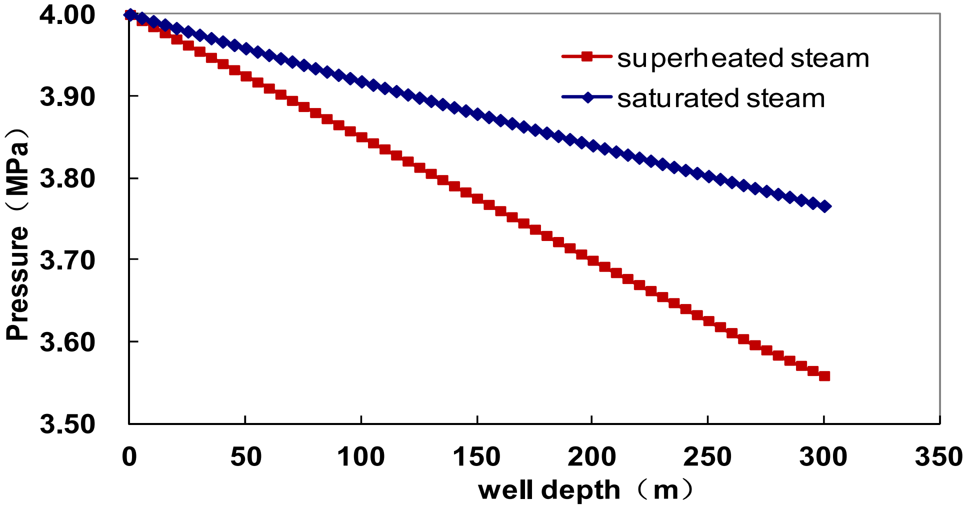


Fig.4 Comparison of pressure distribution along the wellbore

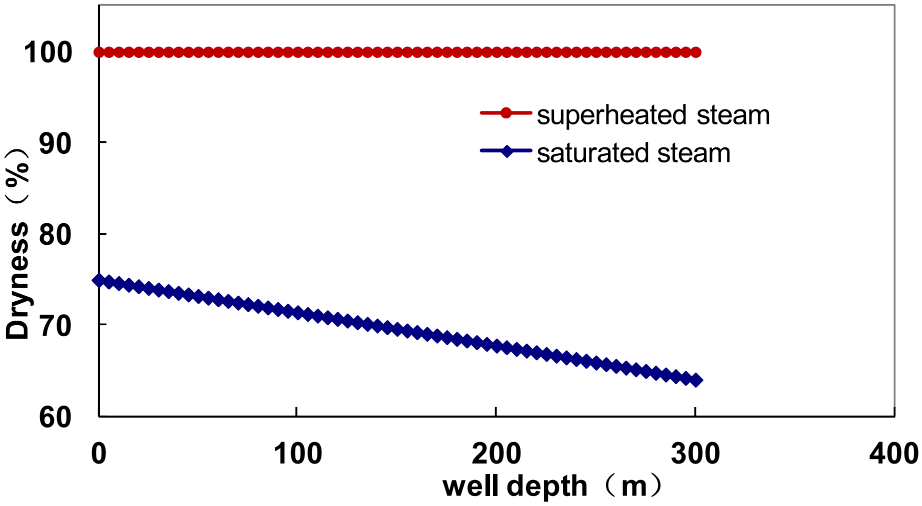


Fig.5 Comparison of dryness distribution along the wellbore

The above calculation results from Fig.3 shows superheat steam has a significant reduction of the superheat degree after arriving at the bottom but the superheated steam still has a higher temperature than saturated steam with 28.8°C superheat degree . Table 4 illustrates heat loss of superheated steam transmission along the wellbore is lower than that of saturated steam and the enthalpy values of superheated steam at the bottom well is 28. 35% higher than that of saturated steam . In addition, after superheated steam reaches the bottom, its pressure is not necessarily higher than the saturated steam. As is shown from Fig.4 and Fig.5 indicate superheated steam is always in the state of the highest dryness of 100%.

Correlations relating different steam injection parameters

Influence of different steam injection pressures

As is shown from Table 5, superheated steam injection pressures are select such as 3.5MPa,3.8MPa,4. 0MPa,4.2MPa,4.5MPa. The state parameters of superheated steam at the bottom hole are shown in table 5. Temperature distribution along the wellbore is shown in Figure 6.

Tab.5 Superheated steam parameters at the bottom well under different steam injection pressures

Injection pressures	Initial enthalpy	Pressures at the bottom well	Temperatures at the bottom well	Dryness at the bottom well	Superheat degree at the bottom well	Enthalpy at the bottom well	Heatloss
（MPa）	（kJ/kg）	（MPa）	(℃)	(%)	(℃)	(kJ/kg)	（kJ/kg）
3.5	2978.78	2.95	269.8	100	34.9	2910.29	68.49
3.8	2968.63	3.32	272.2	100	30.9	2901.7	66.93
4.0	2961.73	3.56	273.6	100	28.4	2895.7	66.03
4.2	2954.74	3.8	275.0	100	26.1	2889.6	65.14
4.5	2944.07	4.13	277.7	100	23.9	2883.6	60.47

Figure 6 makes it clear that with steam injection pressures increase, superheated steam pressures at the bottom hole also increase and the steam temperatures keep in pace with the pressure. But heat loss decrease gradually with injection pressures increase.

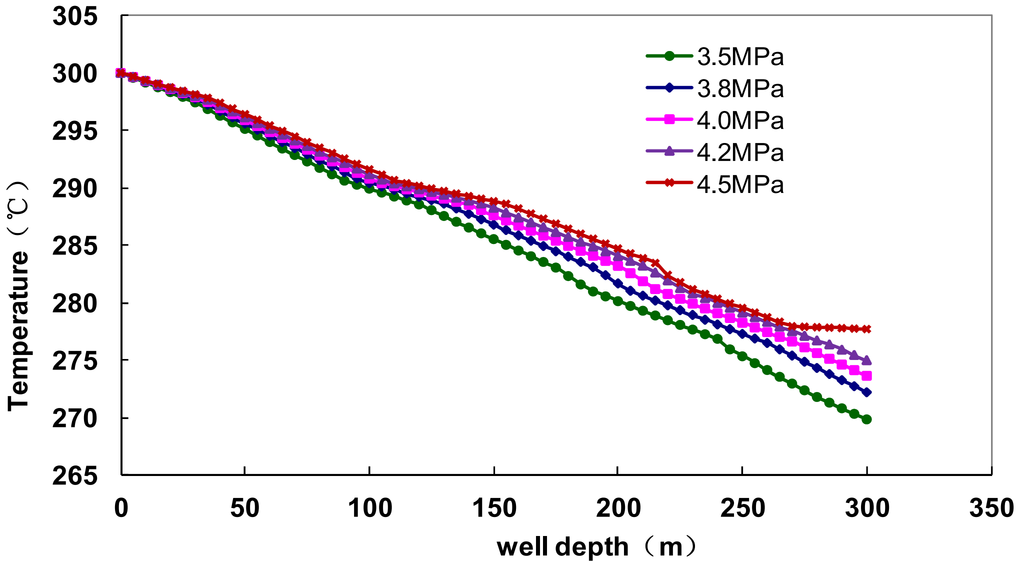


Fig.6 Temperature distribution along the wellbore under different pressures

Influence of different steam injection temperatures

As is shown from Table 6, superheated steam injection temperatures are select such as 280°C,290°C,300°C,310°C,320°C,350°C. The state parameters of superheated steam at the bottom hole are shown in table 5. Temperature variations along the wellbore is shown in Figure 7.

Table 6 Superheated steam parameters at the bottom well under different steam injection temperatures

Injection temperatures	Initial enthalpy	Pressure at the bottom well	Temperatures at the bottom well	Dryness at the bottom well	Superheat degree at the bottom well	Enthalpy at the bottom well	Heatloss
(℃)	（kJ/kg）	（MPa）	(℃)	(%)	(℃)	(kJ/kg)	（kJ/kg）
280	2901.49	3.59	263.2	100	17.5	2861.9	39.59
290	2932.32	3.58	268.4	100	22.9	2878.8	53.52
300	2962	3.56	273.6	100	28.4	2895.7	66.3
310	2989.98	3.54	283.1	100	38.2	2924.5	65.48
320	3017.27	3.52	291.8	100	47.2	2949.9	67.37
350	3094.92	3.48	311.6	100	67.7	3004.7	90.22

Figure 7 makes it clear that with steam injection temperatures increase, superheated steam temperatures at the bottom hole also increase and the steam temperatures keep in pace with the temperature at the wellhead. But heat loss increase gradually with injection temperatures increase.

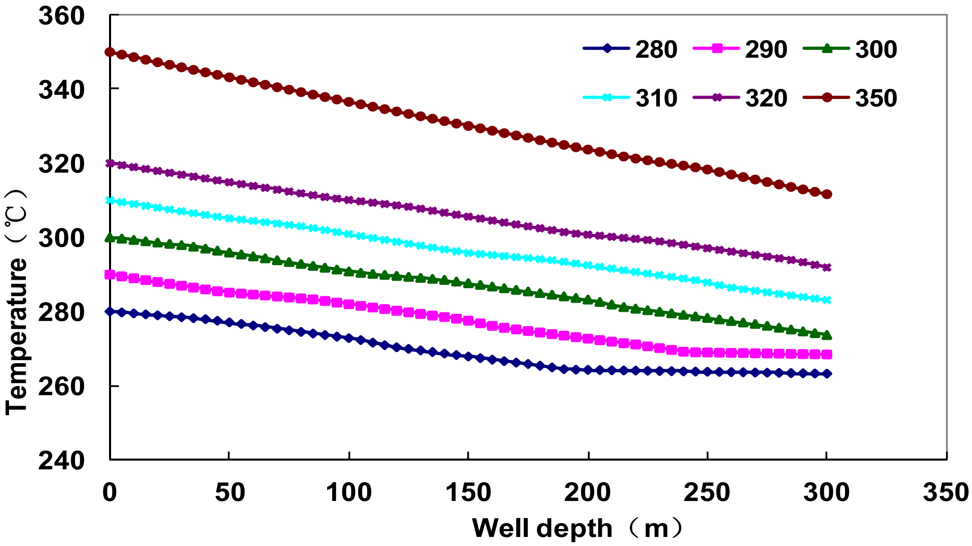


Fig.7 Temperature variations along the wellbore under different temperatures

4 Superiority of Superheated Steam huff and puff

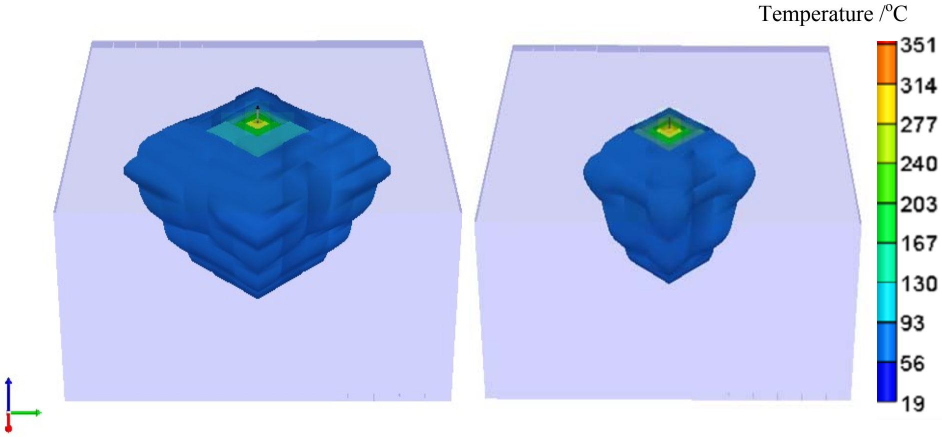
A three dimensional simulation model was built using CMG STARS and was tuned with experimental data from the sub-salt oil reservoir. The model consisted of a vertical matrix block divided into 18 grids in Z direction, 50 grids block in X direction, and 50 grids block in Y direction. Total matrix block length was 200m with 18m of width and depth in X and Z directions. The simulation model is homogenous and the parameters are from the log interpretation results. After a production history matching, model recovery factor of 11.3%, the average remain oil saturation was 57.7%.

In order to analysis the effects of different steam huff and puff, several different types of steam which carried the same quantity of heat and had different temperatures, dryness and degree of superheat were injected into the same oil reservoir under the same pressure of 3MPa. For the first cycle, the quantity of steam injected and cumulative oil production for different steam huff and puff were shown in Table 5. Superheated steam huff and puff results in significantly greater production. After roughly 700 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 4050t and the OSR is 1.8 at 700 days. The cumulative oil production is 1463t greater than that of saturated steam due to extra oil production associated with the injection of superheated steam, which reflected the superiority of superheated steam huff and puff ,which was shown from Table 7.

Figure 8 demonstrates an important dependence on type of steam 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. The heat radius of superheated steam in the first cycle reached 30m, about 10 meters larger than that of saturated steam.

Table 7 Different steam carried the same heat huff and puff effects

Temperature /°C	dryness /%	Degree of superheat / °C	Duration /d	Cyclic injection /t	Cyclic production /t	OSR /fraction
236	40	0	700	3716	1713.7	0.46
236	60	0	700	3114	1720.1	0.55
236	80	0	700	2680	1980.6	0.74
236	100	0	700	2352	2587.2	1.10
286	100	50	700	2250	4050.0	1.80



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

Figure 8 distribution of temperature after the same heat of different steam injection in one cycle

5 RESULTS AND CONCLUSIONS

Superheated steam exists at the temperature higher than that of its saturated steam without the limitation of the pressure, which has a higher temperature, carries more heat and has greater heating capacity than saturated steam. Superheated steam is always in the state of the highest dryness of 100%, which determines that it has a very small heat transfer coefficient. In theory, the heatloss of superheated steam during transmision in wellbores is 1/150-1/250 as much as that of saturated steam,which means that much more heat carried to heat oil reservoir and at the same time it reach further distance for superheated steam. Under the condition of carrying the same heat, heating radius by superheated steam huff and puff is about 10m longer than saturated steam. Superheated steam huff and puff was put into Kazakstan’s heavy oil reservoir after saturated steam huff and puff and the average daily oil production was 2-4 times that of saturated steam huff and puff, which improved heavy oil production effectively.Superheated steam huff and puff as a secondary thermal recovery are very appropriate for difficultly developed heavy oil reservoir.

NOMENCLATURE

Q – Heat transferred rate of fluids, w；

Q_{sup} – Heat transferred rate of superheated steam, w；

Q_s – Heat transferred rate of saturated steam, w；

A –Heat transfer area, m^2；

T_{sup} – Temperature of superheated steam, K；

T_s – Temperature of saturated steam, K；

$T_{\triangledown}$ – Degree of superheat, K；

T_w – Temperature of heat transfer surface , K；

α – Heat transfer coefficient of fluids, W/（$m^2 \cdot K$）

α_{sup} - Heat transfer coefficient of superheated steam, W/（$m^2 \cdot K$）

α_s -Heat transfer coefficient of saturated steam, W/（$m^2 \cdot K$）

ρ_1， ρ_2 —Steam density of into and out of micro element of wellbore, kg/m^3；

ρ_m -- Steam density of all micro element of wellbore, kg/m^3；

v_1, v_2 —Steam injection rate of into and out of micro element of wellbore, m / s；

i_s —Steam mass flow rate，kg/s ;

A —Area of tubing，m^2；

p —Steam pressure of micro element of wellbore,Pa；

Q —Heat transmision, W；

h_m —Enthalpy of superheated steam，J /kg；

θ —Trend angle of deviation

C_p —Heat capacity at constant pressure，J/(kg.K)；

t_s —Temperature of saturated steam, ^oC ;

p_s —Pressure of saturated steam，MPa ;

z —Well depth，m；

REFERENCES

[1] Zhang Yitang, Li Xiuluan, Zhang Xia, et al. “Four fundamental principles for design and follow-up of steam flooding in heavy oil reservoirs”[J]. *Petroleum Exploration and Development*, 2008, 35(6): 715-719.
[2] Wu Xianghong*, Xu Anzhu, Fan Hailiang, “An integrated evaluation on factors affecting the performance of superheated steam huff and puff in heavy oil reservoirs”[J]. *Petroleum Exploration and Development*, 2010, 37(5):608-613.
[3] Qu Tongci, Li Shuang. “Technique of enhancing recovery of remaining oil in heavy oil reservoirs by horizontal wells”[J]. *Petroleum Exploration and Development*, 2009, 36(6): 743-748.
[4] Yan Ke, Ren Huaiqiang. “Oil/water inversion and juxtaposition in heavy oil reservoirs”: Taking 6-7 sand members of Guantao Formation, Gudao Oilfield as an example[J]. *Petroleum Exploration and Developmen*t, 2009, 36(5): 635-640.
[5] Heins B, Xie Xiao, Yan Dengchao. “New technology for heavy oil exploitation wastewater reused as boiler feedwater”[J]. *Petroleum Exploration and Development*, 2008, 35(1): 113-117.
[6] Chang Yuwen, Zhang Yi, Hu Yongjiu, et al. “*The progress of heavy oil thermal recovery technology*”[M]. Beijing: Petroleum Industry Press, 1997.
[7] The International Association for the Properties of Water and Steam.IAPWS-IF97 International Formulation 1997 for the Thermodynamic Properties of Water and Steam [R].Erlangen, Germany, 1997.
[8] Rohsenow, Warren M, et al. “Application of Heat Transfer Handbook”[M]/Book1. Beijing: Science Press, 1992.102-135.
[9] Shen Weidao, Jiang Zhimin, Tong Jungeng. “*Engineering thermodynamics*” [M]. Beijing: Higher Education Press, 2000. 212-229.
[10] Li Chuntao, Qian Genbao, Wu Shuhong, et al. “The property of superheated steam and its application in the development of heavy oil reservoirs: Kenkiyak Oil Field in Kazakhstan as an example”[J]. *Xinjiang Petroleum Geology*, 2008, 29(4): 495-497.
[11] Chen Minfeng, Lang Zhaoxin, Mo Xiaoguo. “Optimization of steam stimulation injection parameter and the reasonable development limits of ultra-heavy oi”l[J]. *Journal of the University of Petroleum, China(Edition of Natural Science)*, 2002, 26(1): 39-42.