Significant Superiorities of Superheated Steam in Heavy Oil Thermal Recovery

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Abstract

With superheated steam there is no direct relationship between temperature and pressure, and it can exist at a wide range of temperatures. Superheated steam with high degree(>50 °C) of superheat has similar thermal physical characteristics with ideal gas and the heat transfer coefficient is 1/150-1/250 as much as that of saturated steam during heat transferring. It could release less energy and transmitted longer distances than that of saturated steam in heavy oil reservoirs. Numerical simulation shows that under the condition of carrying the same heat, superheated steam huff and puff enlarged the heating radius by about 10 m, oil production increment by 1463 t, oil steam ratio increase by 0.7. 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. The secondary heavy oil thermal recovery by superheated steam huff and puff applicated in marginal heavy oil reservoirs achieved satisfactory effect.

Key words: Heavy oil; Superheated steam huff and puff; Heat transfer coefficient; Degree of superheat; Ideal gas

INTRODUCTION

After several cycles saturated steam huff and puff in heavy oil reservoirs, the heating radius are typically only 20-30 m, the maximal radius in perfect reservoir is about 50 m (Amani, 2012; Hosein & Singh, 2012; Ma, 2012). 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 cannot 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 (Ma, 2012; Zhang *et al.*, 2008). 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.

1. PROPERTIES OF SUPERHEATED STEAM

Dry saturated steam (dryness of 100%) continue to be heated in the given pressure and the steam temperature will increase above its saturation temperature. The steam superheated by the number of temperature degrees higher than the corresponding saturated steam is defined as superheated steam. The temperature difference between superheated steam and its saturated steam is called degree of superheat (Wu *et al.*, 2010; Chang *et al.*, 1997; IAPWS, 1997). With compared to saturated steam under the same pressure, superheated steam has a higher temperature, carries more heat and has greater heating capacity than saturated steam (Zhang *et al.*, 2008). With saturated steam, temperature is directly proportional to pressure and the steam pressure determines the steam temperature, enthalpy and specific volume; with superheated steam there is no direct relationship between temperature, pressure and the specific heat capacity (Rohsenow *et al.*, 1992; Shen *et al.*, 2000). Therefore at a particular pressure it may be possible for superheated steam to exist at a wide range of temperatures (Hosein & Singh, 2012; Ma, 2012; Zhang *et al.*, 2008; Wu *et al.*, 2010). This is a useful increase in steam energy, enthalpy and specific volume within the limited pressure (Li *et al.*, 2008; Chen *et al.*, 2002). With the same quantity of saturated steam, superheated steam has the capacity of heating the heavy oil reservoir to a higher temperature and a wider scope. Superheated steam huff and puff has the potential superiority to improve thermal recovery effect.

Table 1 displays properties between superheated steam and saturated steam (dryness of 75%) at various pressures.
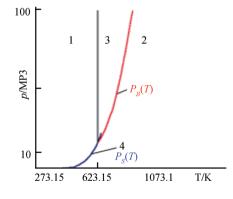
Table 1
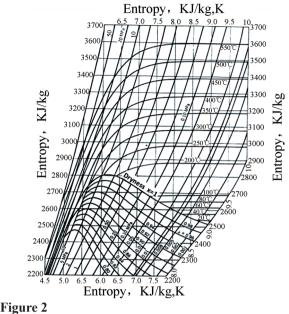**Heat and Volume Multiple of Superheated Steam Compared to Saturated Steam (Dryness of 75%)**

Pressure (MPa)	Saturation temperature (°C)	Degree of superheat (10 °C)		Degree of superheat (50 °C)		Degree of superheat (80 °C)	
		Heat multiples	Volume multiples	Heat multiples	Volume multiples	Heat multiples	Volume multiples
1	184.2	1.23	1.37	1.27	1.52	1.30	1.63
3	235.7	1.20	1.37	1.25	1.55	1.29	1.67
5	265.2	1.19	1.38	1.24	1.58	1.28	1.71
7	286.8	1.18	1.38	1.24	1.62	1.28	1.77
9	304.2	1.17	1.39	1.24	1.66	1.28	1.83
10	311.8	1.16	1.40	1.24	1.69	1.28	1.86

1.1 The Conditions for the Existence of Superheated Steam

In thermodynamics, the presence of water can be defined as four states, such as cold water, wet steam, saturated steam and superheated steam. From the region division, conditions for the existence of superheated steam are wide ranges of temperatures and pressures. Not only at high temperature and high pressure, but also at low temperature and low pressure superheated steam can exist, even at high temperature and low pressure. For saturated steam, the temperature of saturated steam is determined by the pressure (Rohsenow *et al.*, 1992; Shen *et al.*, 2000; Li *et al.*, 2008). But the maximum pressure is limited by steam boiler and burst pressure of the reservoir rock. Therefore, saturated steam temperature increase is limited by the pressure (Chang *et al.*, 1997). But for superheated steam, under a particular pressure, temperature increased to higher than saturated temperature, that is, the state of steam is changed from the saturated region (Region 4) into the superheated steam region (Region 2). As a result, superheated steam can not only increase the temperature of steam, but also increase steam heat carrying. Superheated steam breaks through restrictions of saturated steam in application, and is suitable for thermal recovery of various heavy oil reservoirs.

Region 1 Cold water   Region 2 Superheated steam
Region 3 Wet steam   Region 4 Saturated steam
Figure 1
Regions of Water Phase

Figure 2
H-S Diagram of Steam (Yan, 1985)

1.2 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 °C temperature difference (IAPWS, 1997). 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 (IAPWS, 1997). Figure 2 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 Figure 2 shows the higher the degree of superheat is, and the superheated steam is more close to ideal gas (Li *et al*., 2008), 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 (Chen *et al*., 2002). 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 .

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

$$\frac{Q_{sup}}{Q_s} = \frac{\alpha_{sup} A(T_{sup} - T_w)}{\alpha_s A(T_s - T_w)} = \frac{\alpha_{sup}}{\alpha_s} \cdot \frac{(T_s + T_\Delta - T_w)}{(T_s - T_w)} =$$

$$\frac{\alpha_{sup}}{\alpha_s}(1 + \frac{T_\Delta}{T_s - T_w}) \approx \frac{\alpha_{sup}}{\alpha_s} \tag{2}$$

Table 2
The Value of Heat Transfer Coefficient

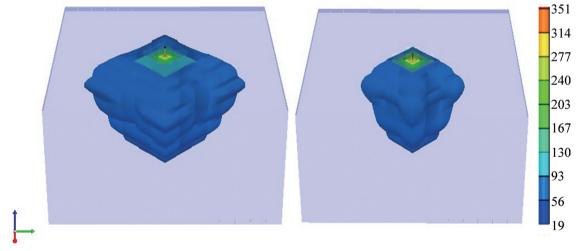| Heat transfer condition	'α' value/ W/(m^2·K)	'α' common use value /W/(m^2·K)
Saturated steam heated or condensed	5000 ~15000	10000
Water boiling	1000 ~30000	3000 ~ 5000
Water heated or cooling	200 ~5000	400 ~1000
Oil heated or cooling	50 ~1000	200 ~ 500
Superheated steam heated or cooling	20 ~100	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

2. PROCESS OF HEAVY OIL RESERVOIRS HEATED BY SUPERHEATED STEAM

The changes of superheated steam can be divided into two stages in heating the heavy oil reservoir. As is shown from Figure 3. The first stage is superheated steam has to cool to saturation steam and the degree of superheat is reduced. When the superheat degree reduced to 0, the superheated steam changes into dry saturated steam, but the steam quality remains at 100%. The second stage is the steam temperature keeps constant and dryness is decreased. In this stage, saturated steam begins to condense to release its enthalpy of evaporation and its phase changes into liquid during the latent heat releasing and become lower dryness saturated steam. When the steam quality reduced to 0, the wet steam changes into hot water, but the steam temperature remains the same with the dry saturated steam. As a result, In the first stage, from the well bore to the edge of superheated steam heating area, the temperature gradually decreased, and there exists temperature gradient in the heating scope and over the heat transfer surface. In the second stage, due to the release of latent heat and the uniform temperature of saturated steam, temperature in saturated steam heating area is keeping constant everywhere. In addition to all saturated steam heating stages, superheated steam has its own superheated stage, in which chemical reactions would happen among formation water, heavy oil, and formation minerals under the favorable circumstances of high temperature of superheated steam. These chemical reactions not only result in some changes of composition and the irreversible reduction of its viscosity, but also change the microscopic pore structure of rocks to improve the permeabilty of superheated steam heating area; changing the wettability of the reservoir rock, increasing the displacement efficiency of superheated steam flooding, which bring about significant improvements of heavy oil development effects.

Figure 3
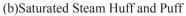**Changes of Superheated Steam in Heating Oil Reservoir**

Figure 4 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 30 m, about 10 meters larger than that of saturated steam.

(a) Superheated Steam Huff and Puff   (b)Saturated Steam Huff and Puff

Figure 4
Distribution of Temperature After the Same Heat of Different Steam Injection in One Cycle

3. PRODUCTION PERFORMANCES OF SUPERHEATED STEAM HUFF AND PUFF APPLICATION

Pilot tests were performed covering 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 1~2 m³/d, which is far from economic limit. Later by saturated steam huff and puff, the average daily production increased to 3 m³/d, which was still not ideal. Two years later by superheated steam huff and puff, the mean daily production was raised to 8~9 m³/d, which increased the daily oil production greatly. The comparison was shown from Figure 5. The production period with superheated steam huff and puff has lasted over 700 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 6.4 t/d, which was 2.8 t/d higher than the saturated steam. Cyclical oil production reached 4160 t by superheated steam huff and puff, which was 2192 t 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.

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, which reflected the superiority of superheated steam huff and puff.

Horizontally, the formation with the temperature of more than 150 °C covers a length of 50~60 m and the steam swept radius is about 30 m. The 10 m greater than that of saturated steam due to extra oil production associated with the injection of superheated steam.
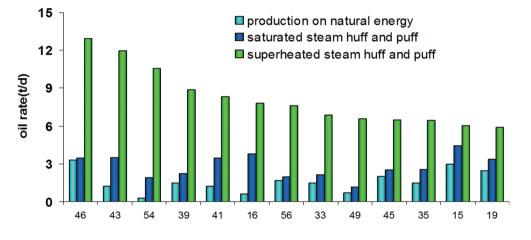

Figure 5
Oil Rate of Single Well Under Three Different Recovery Methods

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. 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 10 m 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, m²
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/(m²·K)

50

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

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

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