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IDENTIFICATION OF THE DEPTH RANGE OF IN SITU SHALE OIL PRODUCTION

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Abstract. *Oil shale resource is an important supplement to conventional oil and gas in China. Thermal in situ retorting processes for producing hydrocarbons from oil shale have been utilized recently. Based on the mechanical analysis of the process of oil shale retorting, for an efficient production of shale oil and gas at least two requirements should be met. Firstly, the expulsion pressure of oil and gas from shale needs to be lower than the breakdown pressure of the overburden interval, to keep the produced oil and gas confined. Secondly, the expulsion pressure of oil and gas should be higher than the breakdown pressure of the shale reservoir to enable the development of more fractures to allow oil and gas to flow. The expulsion pressure of oil and gas from shale is primarily dominated by temperature which means that a vertical or horizontal heater delivery borehole needs place at a proper depth. The higher the heating temperature for in situ shale oil production is, the deeper and thicker the oil shale reservoir should be.*

Keywords: *in situ conversion process (ICP), evaporation pressure, oil shale, reservoir, heating.*

1. Introduction

In China, the oil shale resource is recognized as one of the most abundant energy resources which may contribute to the future domestic oil supply. According to the country's latest petroleum resource assessment, the total shale oil resource of Chinese oil shale is about 47.6 trillion tons. Most oil shale resources are located in big petroliferous basins and about 60% of them are buried at a depth greater than 300 m. Due to high mining costs

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surface retorting method seems not to be suitable for most Chinese oil shales. In situ retorting, by contrast, entails heating oil shale in situ by using downhole heaters [1] and is supposed to be more applicable to Chinese oil shale. However, there are no clear standards for either surface retorting or in situ upgrading. Reservoir depth is most important for resources assessment in case of in situ shale oil production.

2. Conditions for in situ oil shale production

The process of in situ shale oil production consists in converting oil shale kerogen to shale oil by direct (electrical, geothermal, combustion, hot gas injection) or indirect (radio frequency microwaves) heating, causing oil to flow to the production well. Shell Oil Company has developed an in situ conversion process (ICP) for Green River shales of Colorado, which is located in a relatively simple structure sector. The depth of oil shale is about 300–400 m, thickness 260–450 m and oil content 4.7–9.08%. Vertical wells were used for underground oil shale heating at a temperature of 1500 °F (813 °C). The oil and gas recovery ratio could reach 62% [1, 2].

For successful development, the following two basic conditions should be met. Firstly, the production of oil and gas from oil shale should be economically feasible. Secondly, oil and gas should be confined, thus eliminating environmental contamination. So, the structure of the reservoir should be simple and with well-sealed layers. The hydrodynamic system in the reservoir should be independent, in order to avoid environmental contamination and heat loss by contacting adjacent groundwater. The permeability of oil shale matrix under the ground is extremely low, 0.0001–0.000001 md, thus it is very difficult for oil and gas to flow. Therefore fracture is an essential factor in oil and gas production. Only natural fracture is not enough for oil and gas flowing out from oil shale matrix. The pressure of oil and gas with high temperature in the oil shale under the ground is very high. If this pressure is higher than the bursting pressure of oil shale, some new artificial fractures can be formed. Oil and gas can flow along these new fractures to the production well. But if the pressure of oil and gas is higher than the breakthrough pressure of the overlying strata, oil and gas can leak into the surrounding environment. So, it must be assured that the pressure of oil and gas in oil shale is higher than the bursting pressure of the latter and lower than the breakthrough pressure of the overlying strata.

3. Parameters

3.1. Pressure of oil and gas in oil shale

It is supposed that shale oil is produced from oil shale and then gas is produced by evaporation and decomposition. The generation of oil from oil shale is a very complex process, pressure and temperature being the main influencing factors. The effect of temperature is inherent in any chemical reaction. The influence of pressure in a chemical reaction is generally limited to volume change. The process of generating oil from organic matter represents the change of a solid to a liquid, while volume change is negligible. So, this influence can be ignored. The evaporation or cracking of oil into gas is a volume amplifying process and is highly pressure-dependent. In high temperature and high pressure conditions the change of shale oil into gas takes place by both evaporation and pyrolysis. The critical constant prediction method [3] was applied to calculating the vapour pressure of heavy oils and bitumen. Shale oil and heavy oil are similar in component characteristics. So, the method for calculating the vapour pressure of heavy oil presented by Nji *et al*. is used to calculate the vapour pressure [3]. It is expressed by Equation 1 at different temperatures:

$$P_v = P_v^0 \left[\frac{(1+2f)}{(1-2f)} \right]^2, \tag{1}$$

where P_v is the real evaporation pressure of gas, Pa; P_v^0 is the critical evaporation pressure, Pa; f is the disturbance factor.

$$f = a_f \Delta SG^2 + b_f \Delta MW^2 + c_f \Delta SG + d_f \Delta MW + e_f \Delta SW \Delta MW \tag{2}$$

$$\Delta SG = \ln \frac{SG^0}{SG} \tag{3}$$

$$\Delta MW = \ln \frac{MW^0}{MW} \tag{4}$$

$$SG^0 = a + \frac{b}{MW^0} - \frac{c}{(MW^0 + d)^e}, \tag{5}$$

where a_f, b_f, c_f, d_f and e_f are fitting factors; *SG* is the specific gravity of liquid hydrocarbon at 15.6 °C, 1 atmosphere; *MW* is the molecular weight; SG^0 is the specific gravity of the reference component; MW^0 is the molecular weight of the reference component; *a, b, c, d, e* are fitting parameters.

3.2. Bursting pressure of oil shale and breakthrough pressure of overlying strata

3.2.1. Bursting pressure of oil shale

Rock cracking always occurs in the weakest direction. The bursting pressure of the reservoir rock is the sum of the minimum principal stress (σ_3) and the cohesion of the reservoir (tensile strength f_z) (Equation 5). Normally, the maximum principal stress (σ_1) manifests itself in the vertical direction and the minimum principal stress (σ_3) in the horizontal direction. So, the reservoir fractures caused by the high pressure of high temperature oil and gas are mostly developed in the vertical direction:

$$P_f = \sigma_3 + f_z \tag{6}$$

$$\sigma_3 = \gamma \frac{\rho g h}{1-\gamma}, \tag{7}$$

where P_f is the bursting pressure of the rock, MPa; σ_3 is the minimum principal stress of the reservoir, MPa; f_z is the tensile strength of the reservoir rock, MPa; γ is Poisson's ratio; ρ is the average density of the overlying strata, g/cm^3; g is the gravity acceleration, m/s^2; h is the reservoir depth, m.

3.2.2. Breakthrough pressure of overlying strata

For a good closed roof with continuity and no fractures, the breakthrough pressure is the sum of the gravity and structural force of the upper strata.

$$P_{top} = \rho g h_t + f_{zt}, \tag{8}$$

where ρ is the average density of the overlying strata, g/cm^3; g is the gravity acceleration, m/s^2; h_t is the buried depth of the roof, m; f_{zt} is the structural force of the upper strata, Pa.

3.3. Depth range

There are many factors that affect depth range for in situ shale oil production. These include the physical properties of the oil shale reservoir and surrounding rocks, heating well type and well spacing, parameter changes of the heating process, etc. In order to simplify the in situ shale oil production model, it is supposed that the properties of the reservoir and surrounding rock are homogeneous. For in situ shale oil production vertical or horizontal wells are most suited. The heating temperature is up to the performance of the heating system. The electric heater used in the Shell pilot is made of 68% Ni, 20% Cr, 8% Fe, etc. The long-term stable heating temperature of heaters may reach 1500 °F (813 °C) [4]. The temperatures to evaluate the appropriate depth range are 700, 800, 900, 1000, 1100 and 1200 K.

3.3.1. Depth range for vertical wells

The heating temperature along a vertical wellbore is homogeneous at the same radius. The temperature near the wellbore is the highest. The bottom of the buried depth of in situ production is determined by both vapor pressure and bursting pressure. The pressures need meet the following condition:

$$P_v > P_f \tag{9}$$

The top of the buried depth is determined by both vapor pressure and breakthrough pressure. The pressures need meet the following condition:

$$P_v < P_{top} \tag{10}$$

As shown in Fig.1, by combining Equations (1)–(10), the vapor pressure at a temperature of 700, 800, 900, 1000, 1100 and 1200 K is 2.28×10^6, 4.73×10^6, 6.64×10^6, 8.24×10^6, 9.32×10^6 and 10.22×10^6 Pa, respectively. The Poisson ratio of oil shale is 0.25. The average density of the upper stratum is about 2000 kg/m^3. The bottom of the buried depth can be calculated with the depth of 348.98, 723.98, 1016.33, 1261.22, 1426.53 and 1564.29 m, and the top of the buried depth is 116.33, 241.33, 338.78, 420.41, 475.51 and 521.43 m (Fig. 2). Figure 2 shows that the depth range lies between the two lines. The higher the heating temperature is, the deeper and thicker the oil shale reservoir is. So, the production thickness in case of a proper depth range is determined by the length of the heater in the continuous oil shale reservoir. With the above conditions, the effective radiuses are the maximum heating distance to 300 °C, which are 3.75, 6.25, 9.01, 11.83, 14.91 and 18.46 m, calculated by the MATLAB 7.0 PDE Toolbox by using Equation 11. The result shows that the heating area is very small. So, a small well spacing is needed in case of the vertical well heating:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - q \, , \tag{11}$$

where ρ is the density of oil shale, kg/m^3; C_p is the specific heat of oil shale, J/kg·k; T is the temperature, K; t is the time, d; k is the thermal diffusion coefficient of oil shale, m^2/d; z is the oil shale vertical heating distance, m; q is the heat from the oil shale reservoir, J/d.

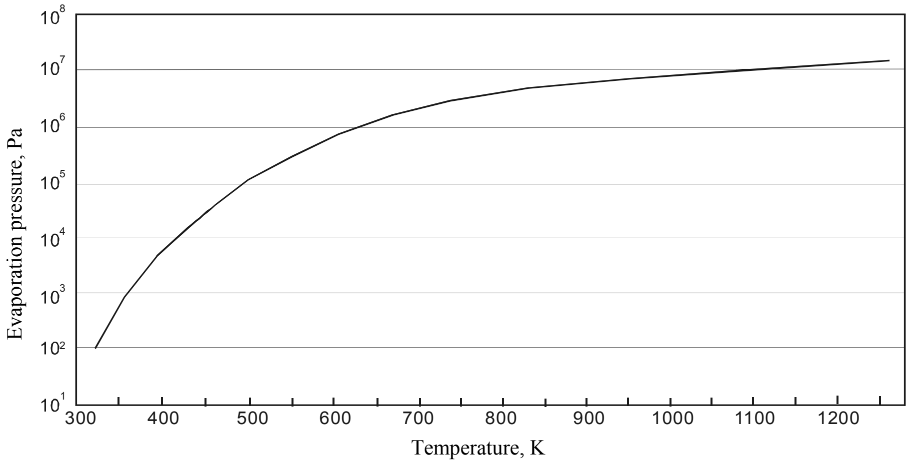

Fig. 1. Evaporation pressure curve of shale oil and gas at different temperatures.

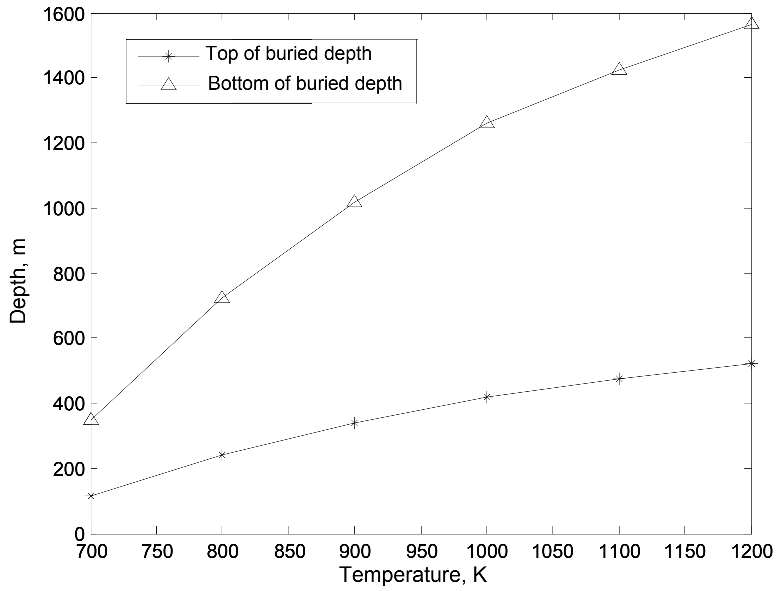

Fig. 2. Appropriate depth range of in situ shale oil production by vertical well heating.

3.3.2. Depth range for horizontal wells

It is supposed that the horizontal parts of horizontal wells are on the same horizontal plane. Vertical and horizontal wells differ in temperature distribution. The temperature decreases along the radial direction and remains almost constant parallel to the well borehole. Considering the temperature distribution with a horizontal well, the top of the buried depth is determined by the pressure of oil and gas at the minimum temperature. If 300 °C is the minimum temperature of oil shale conversion to oil and gas, the corresponding depth is 22.35 m with the breakthrough pressure. If at a buried depth of 22.35 m the oil shale temperature is no higher than 300 °C during the whole heating cycle, this condition can be met. So, the buried depth of the horizontal well should be the sum of the maximum vertical heating distance to 300 °C and 22.35 m.

By long-time heating, oil and gas can be produced from oil shale at about 300 °C [2]. The Nenjiang oil shale of the Songliao Basin, China, with the density of 1960 kg/m^3, thermal diffusion coefficient 0.0084 cm^2/s and specific heat 1597 J/kg·k, served as a sample. The PDE Tool Box of MATLAB was used to calculate Equation 11. The effective thickness (with oil shale temperature above 300 °C) above the well is 17.5, 23, 27.8, 31, 33.4 and 34 m by heating at 700, 800, 900, 1000, 1100 and 1200 K, respectively, in 2000 days with a 30 m well distance. Adding 22.35 m, the top of the buried depth at different temperatures is 39.85, 45.35, 50.15, 53.35, 55.75 and 56.35 m (Fig. 3). The maximum temperature of in situ shale oil production with the horizontal well is the heating temperature. So, the bottom depth of the horizontal well is the same as that of the vertical well (Fig. 3). Heating with horizontal wells on a horizontal plane, the effective heating thickness includes both sides of the plane and is 35, 46, 55.6, 62, 66.8 and 68 m. For in situ shale oil production, the appropriate depth and effective heating thickness increase with increasing heating temperature.

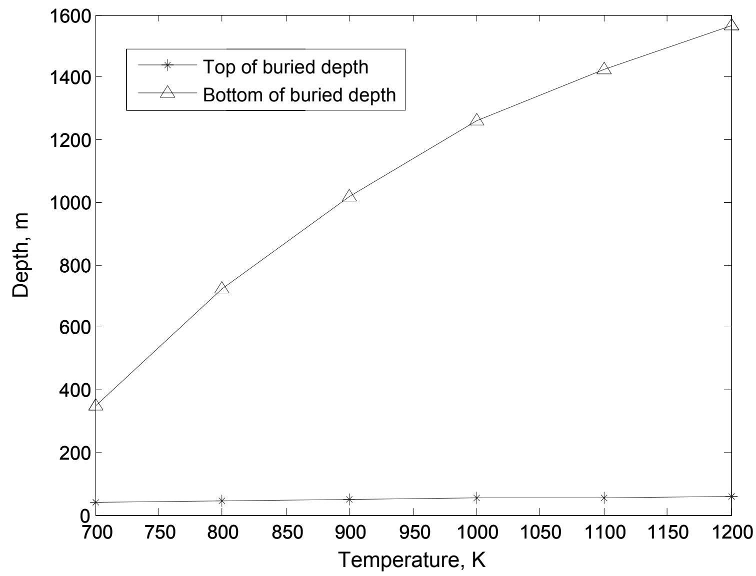

Fig. 3. Appropriate depth range for in situ shale oil production by horizontal well heating.

4. Conclusions

The heating thickness of in situ shale oil production with a vertical well is determined by the length of the heater, but the effective heating area is very limited. So, heating with a vertical well usually suits an oil shale with great thickness, such as the Green River oil shale in the USA.

By horizontal well heating the heating area is effectively expanded, but the effective heating thickness is very limited. So, heating with a horizontal well usually suits an oil shale with small thickness and large area, such as the Green River oil shale in the USA. The oil shales in China were mostly deposited in lacustrine facies and the thickness is generally from 10 to about 15 m, such as the oil shale in the Orodos and Songliao basins. So, for the in situ shale oil production, heating with a horizontal well is suitable for Chinese oil shale.

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