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Effects of Fluid Saturation and Porosity on the Estimation of Geothermal Resources in Oil and Gas Reservoirs

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ABSTRACT

The effects of oil and gas saturation on geothermal resource were considered in previous study. However it was assumed that the oil and gas saturations were constant during the development. To this end, the existing volumetric approaches of evaluating geothermal resource were modified by considering the change of oil and gas saturation with time. An oil reservoir from Huabei oil field with moderately high temperature was chosen as an example to apply the modified method. The effects of porosity, oil and gas saturation on the geothermal resource were investigated and the results were compared to the existing approaches.

1. INTRODUCTION

The direct use of geothermal energy and power generation by using hot fluids co-produced from oil and gas reservoirs is increasingly important as it is environmentally friend price (Erdlac, et al., 2006, 2007; Li, et al., 2007; McKenna, et al., 2005; Milliken, 2007). It is of importance to evaluate the geothermal resource in oil and gas reservoirs accurately. A number of approaches could be used to determine the capacity of a geothermal system. These include volumetric, analytical and numerical approaches. In this study, we focus on the volumetric approach to estimate geothermal resources in oil and gas reservoirs.

The estimation of geothermal resource in oil and gas reservoirs differs from that in geothermal reservoirs as there are differences between geothermal and petroleum reservoir engineering (Yan and Yu, 2000; Sanyal, 2003 and 2007; Sanyal and Sarmiento, 2005; Ciptomulyono, 2007; Zhang et al., 2009). Zhang et al. (2009) modified the volumetric approach by including three phases (oil, water and gas). However, in their study, the values of the oil and gas saturation were assumed constant from the beginning to the end of the development of the reservoir, which is obviously not the case. During the development of oil reservoirs, the water saturation may increase while the oil and gas saturations decrease. This makes the mean specific heat of fluids resided in the rock increase. With all of the above considerations, we modified the volumetric method by considering the saturation change during the development of oil and gas reservoirs.

2. THEORY

The volumetric approach is widely used in geothermal engineering since it doesn't need much information to conduct as other sophisticated evaluation approaches (Clotworthy et al., 2006). To consider the effects of oil and gas saturation on the geothermal resource in petroleum reservoirs with both oil and gas phases, the volumetric method is described as follows (Zhang et al., 2009):

$$Q_R = A \cdot h \cdot (T_r - T_a) \cdot \overline{C} \tag{1}$$

Where Q_R is the total available heat resource of the geothermal system, A is the area of the geothermal reservoir, h is the reservoir thickness, T_r is the initial temperature of the geothermal reservoir, and T_a is the abandonment temperature of the reservoir, $\overline{C}$ is the mean specific heat of rock and fluids resided in the rock, and can be expressed as:

$$\overline{C} = \rho_c \cdot C_r \cdot (1-\phi) + (\rho_w \cdot C_w \cdot S_w + \rho_o \cdot C_o \cdot S_o + \rho_g \cdot C_g \cdot S_g)\phi \tag{2}$$

$$S_w + S_o + S_g = 1 \tag{3}$$

Where ρ_r , ρ_g , ρ_w and ρ_o are the density of rock, gas, water and oil respectively, C_r, C_g, C_w and C_o are the specific heat of rock, gas, water and oil respectively, Φ is porosity of rock, S_w, S_o and S_g are the saturation of water, oil, and gas.

Note that the volumetric approach above doesn't consider the saturation alteration during the development of oil and gas reservoirs. However the water saturation increases while the oil and gas saturations decrease when the development of oil reservoirs approaches to the phase of abandonment. Taking the saturation alteration into account, the volumetric model is modified and is expressed as follows:

$$Q_R = Q_i - Q_a \tag{4}$$

Where Q_i is the initial heat resource of the geothermal system, Q_a is the heat resource of the geothermal system at the abandonment time, Q_i and Q_a can be calculated as:

$$Q_i = AhT_r\overline{C_i} \tag{5}$$

$$Q_a = AhT_a\overline{C_a} \tag{6}$$

Where $\overline{C_i}$ is the initial mean specific heat of rock and fluids resided in the rock, $\overline{C_a}$ is the mean specific heat of rock and fluids resided in the rock at the abandonment time, $\overline{C_i}$ and $\overline{C_a}$ are expressed as follows:

$$\overline{C_i} = \rho_r c_r (1-\phi) + \rho_w c_w \phi S_{wi} + \rho_o c_o \phi S_{oi} + \rho_g c_g \phi S_{gi} \quad (7)$$

$$\overline{C_a} = \rho_r c_r (1-\phi) + \rho_w c_w \phi S_{wa} + \rho_o c_o \phi S_{or} + \rho_g c_g \phi S_{ga} \quad (8)$$

$$S_{wi} + S_{oi} + S_{gi} = 1 \quad (9)$$

$$S_{wa} + S_{or} + S_{ga} = 1 \quad (10)$$

Where S_{wi}, S_{oi} and S_{gi} are the initial saturation of water, oil and gas, S_{wa}, S_{or} and S_{ga} are the saturation of water, oil and gas at the abandonment time.

In addition, the electric energy (power) generated from geothermal energy can be described as:

$$E = Q_R \cdot \eta \quad (11)$$

Where η is the efficiency factor, E is the electric energy generated from geothermal energy.

3. RESULTS

In this study, Hexaw reservoir in Huabei oilfield (150 kilometers south of Beijing, China) is chosen as a case study of the modified volumetric approach. Hexaw oil reservoir is located in Hexaw structural belt in Lang-gu depression. It is one of the main water flooding carbonate reservoirs of Huabei oilfield. The basic geological data of Hexaw reservoir, including formation thickness, porosity, reservoir rock density, specific heat and formation fluid specific heat, are listed in Table 1.

Table 1: The basic geological data of Hexaw reservoir in Huabei oilfield.

area (A, km^2)	452
thickness (h, m)	117
porosity (φ, %)	30
density of rock (ρ_r, kg/m^3)	1956
specific heat of rock (C_r, J/(kg·°C))	857
density of oil (ρ_o, kg/m^3)	850
specific heat of oil (C_o, J/(kg·°C))	2468
density of water (ρ_w, kg/m^3)	1000
specific heat of water (C_w, J/(kg·°C))	4190
density of gas (ρ_g, kg/m^3)	0.717
specific heat of gas (C_g, J/(kg·°C))	2227

Using both the volumetric approach (Eqs. 1-3) and the modified volumetric approach (Eqs. 4-10), we calculated the geothermal resource, energy and the possible income from Hexaw reservoir. In the calculation, the efficiency factor is set as 12% and the price of energy is 0.5 Yuan/kW.h (1 dollar = 7 Yuan approximately).

Figure 1 shows the effect of water saturation on the geothermal resource in the case in which only oil and water phases exist in the oil reservoir (T_r=120 °C). The porosity of the reservoir was assumed to be 30% in this case. The geothermal resource increases with water saturation and decreases with the increase in oil saturation significantly. The geothermal resource evaluated by the modified volumetric method is less than that calculated by the volumetric method (Zhang et al., 2009). As water saturation decreases, the difference between the geothermal resources calculated by Eqs. 1 and 4 becomes increasingly significant. When the water saturation approaches to 1, the difference approaches to zero as expected. This observation is reasonable because the specific heat of oil is less than that of water. We can see from Figure 1 that the geothermal resource in oil reservoir is overestimated if the saturation alteration is simply neglected as in the existing volumetric approach, especially in the reservoir with high oil saturation.

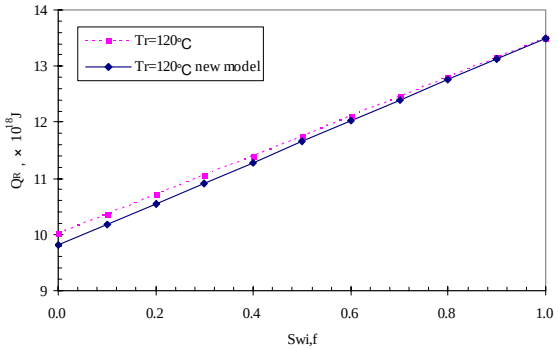

Figure 1: Effect of water saturation on the geothermal resource in the case in which only oil and water phases exist in the oil reservoir (T_r=120°C, ϕ =30%).

Figure 2 shows the effect of water saturation on the power in the case in which only oil and water phases exist in the oil reservoir (T_r =120 °C). It can be seen from Figure 2 that the energy generated increases with water saturation and the energy evaluated by the existing volumetric method is overestimated. The effect of water saturation alteration during the development of the oil reservoir on the power is more significant at higher oil saturation.

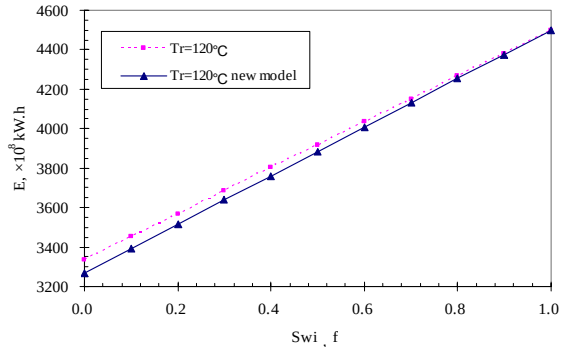

Figure 2: Effect of water saturation on the power generation in the case in which only oil and water phases exist in the oil reservoir (T_r=120°C, ϕ =30%).

Figure 3 shows the possible income at different water saturation in the case in which only oil and water phases exist in the oil reservoir (T_r =120 °C). It is obvious that the income increases with water saturation, and the possible income evaluated by the modified volumetric method is less than that of volumetric method as well. Comparing the two models, the trend of overestimating the income by the existing model is more significant at a higher oil saturation calculated by the modified volumetric approach.

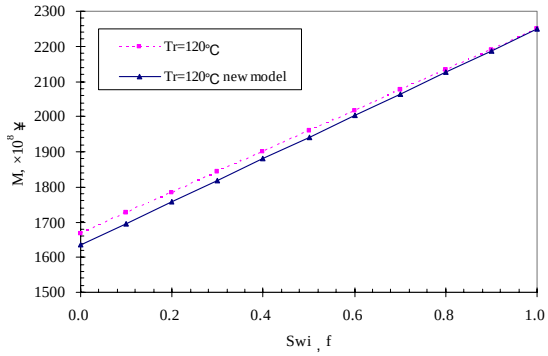

Figure 3: Effect of water saturation on the possible income in the case in which only oil and water phases exist in the oil reservoir (T_r=120°C, ϕ =30%).

It can be seen from Figures 1-3 that the rates of geothermal resource, power, and the possible income calculated by the modified volumetric approach increasing with water saturation are greater than that by the existing volumetric method. Comparing to the modified volumetric method, the existing volumetric method overestimates the geothermal resources, especially at high oil saturation.

Figure 4 shows that the effect of water saturation on the geothermal resource in the case in which only oil and water phases exist in the oil reservoir at different reservoir temperatures (120, 160, and 180°C). The porosity of the reservoir was also assumed to be 30% in this case. One can see from Figure 4 that the geothermal resources calculated by the modified model increase with the reservoir temperature. As the temperature of the reservoir increases, the effect of water saturation on the geothermal resource is more significant.

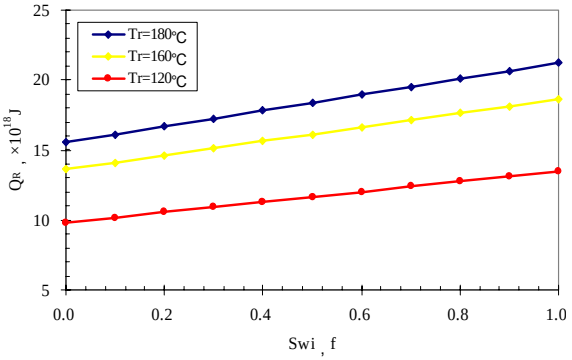

Figure 4: Effect of water saturation on the geothermal resource in the case in which only oil and water phases exist in the oil reservoir (ϕ=30%).

Figures 5, 6, and 7 show the effects of water saturation on the geothermal resource, power, and possible income at a reservoir temperature of 120 °C in the case in which only gas and water phases exist in the gas reservoir.

Figure 8 show the effect of water saturation on the geothermal resource in the case in which only gas and water phases exist in the gas reservoir at different temperatures (120, 160, and 180°C).

One can see that from Figures 5-8 the effect of water saturation on the geothermal resource, power, and possible income in the case in which gas and water phases exist in the reservoir are similar to those observed in Figures 1-4 in oil reservoirs.

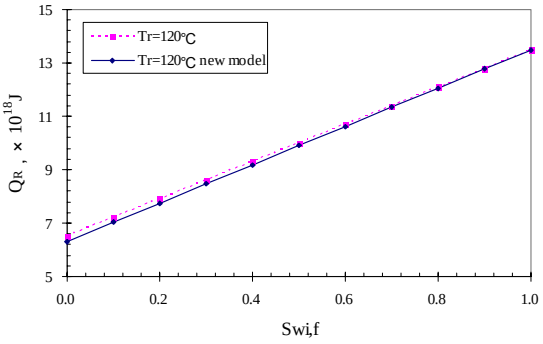

Figure 5: Effect of water saturation on the geothermal resource in the case in which only gas and water phases exist in the gas reservoir (T_r=120°C, ϕ =30%).

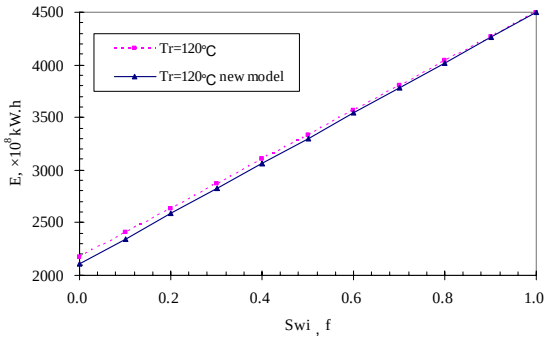

Figure 6: Effect of water saturation on the power in the case in which only gas and water phases exist in the gas reservoir (T_r =120°C).

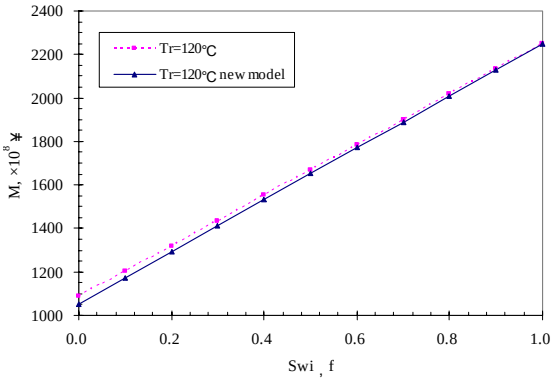

Figure 7: Effect of water saturation on the possible income in the case in which only gas and water phases exist in the gas reservoir (T_r=120°C).

Figure 9 shows the comparison of the effect of water saturation on the geothermal resource between oil-water (oil reservoir) and gas-water (gas reservoir) systems at the temperature of 120°C. As shown in Figure 9, the geothermal resource in oil-water system is greater than that in gas-water system at the same reservoir temperature and the same water saturation. This is because the specific heat of gas is lower than that of oil. The rate of the geothermal resource increasing with water saturation in gas-water system is greater than that in oil-water systems. Furthermore, the rate of geothermal resource increasing with water saturation calculated by the modified volumetric

approach is greater than that of the volumetric method proposed by Zhang et al. (2009). As water saturation decreases, the difference between two models becomes more significant while the difference approaches to zero when water saturation is 1.

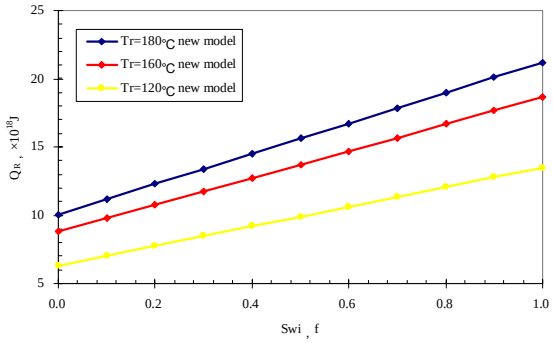

Figure 8: Effect of water saturation on the geothermal resource in the case in which only gas and water phases exist in the gas reservoir.

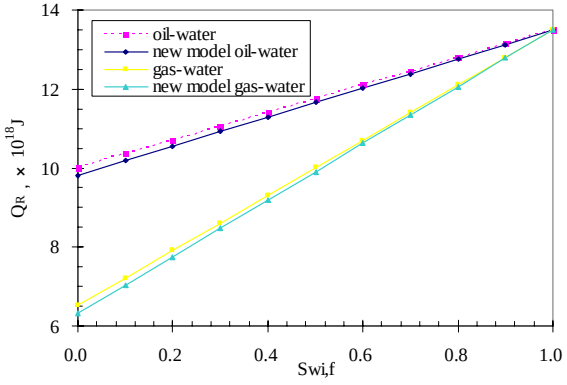

Figure 9: Comparison of the effect of water saturation on the geothermal resource between oil-water and gas-water systems (T_r=120°C).

The above results are based on the porosity of 30%, which is the mean porosity of Hexaw reservoir in Huabei oilfield. However, as we know, the values of porosity vary in different geothermal and petroleum reservoirs. To study the effect of porosity on the geothermal resource, we calculated geothermal resources using different porosity values other than 30%, that is, 5% and 15%. Figures 10-12 present the results.

Figure 10 shows that the effect of water saturation on the geothermal resource with a porosity of 15% in the case in which only oil and water phases exist in the reservoir, and Figure 11 shows the result calculated with a porosity of 5%. As porosity decreases, the difference between the two models becomes less significant. There is almost no difference between the two models because of the very small value of porosity (see Figure 11). It can be seen from Figures 10 and 11 that the effect of water saturation on the geothermal resource in low porosity reservoirs is less significant than that in high porosity reservoir. All of the results are summarized in Figure 12.

The similar calculations at different values of porosity for gas-water system were also calculated and the similar results were observed.

According to the above results, the effect of water saturation on the geothermal resource may be neglected when the porosity is small enough.

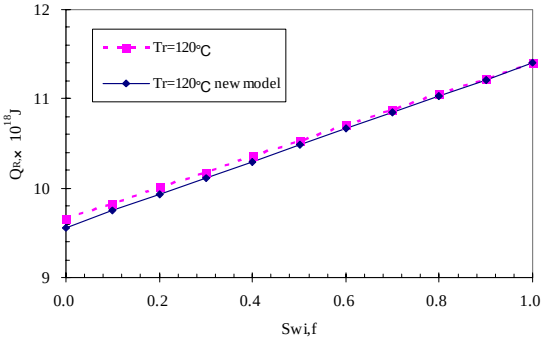

Figure 10: Effect of water saturation on the geothermal resource in the case in which only oil and water phases exist (ϕ=15%).

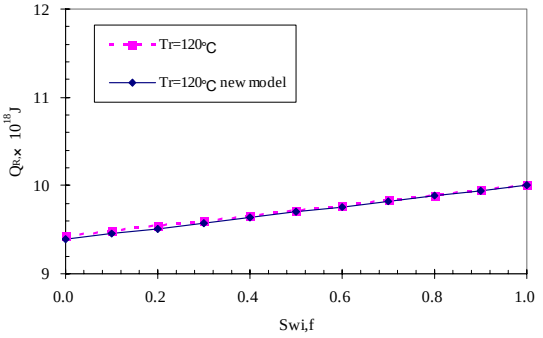

Figure 11: Effect of water saturation on the geothermal resource in the case in which only oil and water phases exist (ϕ=5%).

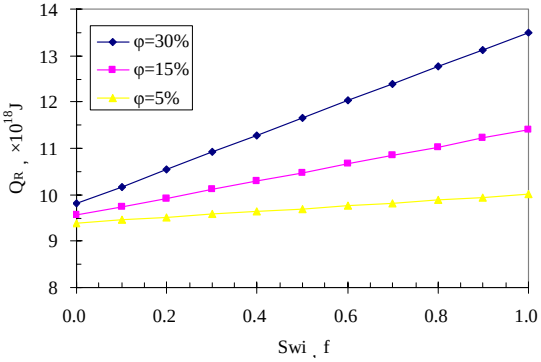

Figure 12: Comparison of the effect of porosity on the geothermal resource in oil-water system (T_r =120°C).

Oil and gas reservoirs may have different rock types, such as sandstone, carbonate, and shale. The values of the specific heat of different rocks are different because of their different mineral compositions. We conducted the calculation for oil-water systems at the temperature of 120°C using the different values of specific heat of rock. The results are shown in Figure 13. The geothermal resource increases with the value of specific heat of rock greatly. This indicates that the rock type plays an impact role in determining the geothermal resource.

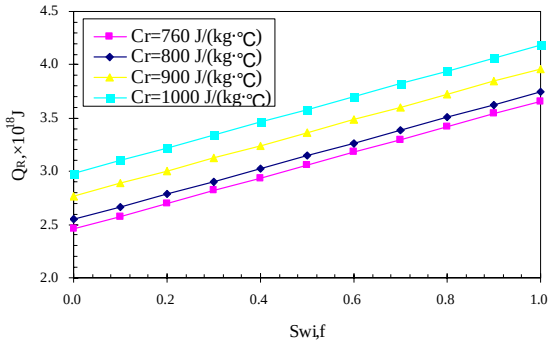

Figure 13: Comparison of the effect of rock types on the geothermal resource in oil-water system (T_r=120°C, ϕ=30%).

4. CONCLUSIONS

The following conclusions may be drawn according to the present study:

Comparing to the modified volumetric approach, the geothermal resource, energy, and possible income are overestimated by the existing model. It is necessary to consider the effects of saturation alteration during the development of oil and gas reservoirs on the estimation of geothermal resource.

The difference in estimating the geothermal resource between the two models is more significant as the oil or gas saturation is greater, that is, the greater the oil or gas saturation is, the more the overestimation of the geothermal resource is.

The difference between the modified volumetric approach and the existing model becomes less significant as the value of porosity decreases, and it can be neglected when the porosity is less than a specific value.

The effect of specific heat of rock on the geothermal resource is significant and may not be ignored in some cases.

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