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Study on Calculation Method of Low and Medium Temperature Geothermal Well Bottom Pressure

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ABSTRACT

Low-Medium temperature geothermal field is widely distributed in China, and geothermal resources are abundant. Well test is an important means of determining geothermal reservoir reserve and geothermal well productivity. However, in well test process, dynamic water level is often higher than static water level, and the abnormal water level difference cannot be used to calculate geothermal well productivity. In order to solve this problem, the paper firstly derives equation for calculating well bottom pressure by integral method. Taking measured geothermal well temperature and water level data as an example, dynamic water pressure and hydrostatic pressure of a geothermal well bottom are calculated by integral method. In addition, the calculation results were compared with those obtained by average density method and segmentation method. The comparison results showed that whether static water level is higher than dynamic water level or dynamic water level is higher than static water level, dynamic water pressure at bottom of the geothermal well is less than hydrostatic pressure. Therefore, when calculating geothermal well productivity, pressure difference of geothermal well bottom is more reasonable and more accurate than water level difference. The results showed that integral method objectively reflects continuous characteristics of down-hole temperature distribution, and is more accurate than average density method and segmentation method to calculate geothermal well bottom pressure.

1. INTRODUCTION

China is rich in medium-low temperature geothermal resources, and its karst geothermal reservoir is the most important geothermal reservoir in China due to its wide distribution, shallow burial, large water volume and high temperature. Fully and efficient development of China's karst geothermal reservoir can play a very significant role in energy conservation and emission reduction.

Geothermal well test is very important in the development of karst geothermal reservoir, and it is an important means to determine production capacity of geothermal fields. In the mid-low temperature geothermal well test process, it is often found that dynamic water level is higher than static water level. It is more difficult to directly calculate geothermal reservoir parameters and geothermal well production capacity by using water level data. In this case, down-hole pressure measurement is required to obtain well bottom pressure. However, in actual work, direct measurement of well bottom pressure requires a corresponding cost. Especially in deep well operations, measuring well bottom pressure requires very high requirements on the instrument, and the cost of input is also large. Therefore, if well bottom pressure can be calculated by using relatively easy to measure geothermal well temperature and water level data, the workload and capital investment will be greatly reduced.

Chen et al. (1997) used a pressure measuring instrument to measure the bottom pressure of a deep geothermal well and compared it with the calculated pressure value. The calculation results showed that well pressure calculation results considering change of geothermal fluid density showed a very good linear relationship with well bottom pressure measurement results, which proved that well bottom pressure can be calculate by water level. Chen et al. (1998) and Zhou et al. (2000) calculated hydrostatic pressure and hydrodynamic pressure of the geothermal well bottom by using average density method, and compared with observation results for many years. The comparison results showed that change in well bottom pressure can well reflect impact of production on geothermal reservoir pressure. Zhao et al. (2011) assumed that water temperature at wellhead was linearly distributed to the bottom water temperature, and geothermal well bottom pressure was calculated by the piecewise calculation method. Previous studies have laid a very important basic reference for the calculation of geothermal well bottom pressure and the acquisition of geothermal reservoir parameters.

In the past, method used to calculate the geothermal well bottom pressure is basically average density method or the further refinement of average density method. The basic idea is to divide down-hole water column and then calculate approximate solution of well bottom pressure. Considering that the change in temperature of geothermal fluid in the well is continuous, change in density is also continuous. If the relationship between temperature of down-hole fluid and depth of well can be obtained, the integral method can be used to calculate pressure generated by geothermal fluid on the bottom of well under the continuous change of density, which is the most accurate in theory and applications. In this paper, we will derive calculation formulas of integral method, average density method and segmentation calculation method, and compare and analyze the accuracy and application of various methods.

2. INTEGRAL METHOD

In general, the density of geothermal water (ρ) is a function of temperature (t), ie $\rho=f(t)$, in a particular geothermal well, the temperature t is a function of well depth x, ie $t=g(x)$. Therefore, in a particular geothermal well, density of geothermal water is also a function of well depth, ie $\rho=f[g(x)]$.

The straight line in the well is taken from center of well surface and the straight line is x-axis (Fig. 1), and the horizontal line at the center of liquid level is y-axis. Take depth x as the integral variable, and its variation interval is [*0, H*]. The height of a thin layer of water corresponding to [*x, x + dx*] between any of the intervals [*0, H*] is dx, and the pressure generated by this thin layer of water is:

$$dP = \rho(\mathrm{x}) g dx \tag{1}$$

The bottom pressure of the well is:

$$P = \int_0^H \rho(\mathrm{x}) g dx = g\int_0^H \rho(\mathrm{x}) dx \tag{2}$$

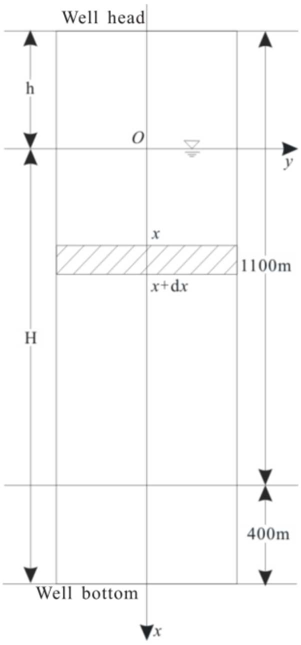

Figure 1: Diagram of geothermal well bottom pressure calculating using integration method

Under static water and pumping conditions, bottom pressure of the well can be expressed as:

$$P_{stat-bottom} = P_{stat} + P_{atm} = g\int_0^{H_{stat}} \rho_{stat}(x)dx + P_{atm} \tag{3}$$

$$P_{dyna-bottom} = P_{dyna} + P_{atm} = g\int_0^{H_{dyna}} \rho_{dyna}(x)dx + P_{atm} \tag{4}$$

Where $P_{stat\text{-}bottom}$ and $P_{dyna\text{-}bottom}$ are well bottom pressure under hydrostatic conditions and pumping conditions, P_{stat} is Pressure generated by water column in wellbore under hydrostatic conditions, P_{dyna} is Pressure generated by the water column in the wellbore under pumping conditions, P_{atm} is Atmospheric pressure acting on the liquid level in the well, ρ_{stat} *and*ρ_{dyna} are density function for calculating hydrostatic pressure at a certain point under hydrostatic conditions, Pumping conditions, g is Gravity acceleration, H_{stat} and H_{dyna} are Water column height under hydrostatic conditions and pumping conditions.

If there is an original function *P(x)* of the continuous function *ρ(x)* on the interval [*0, H*], then according to the Newton-Leibnitz formula (School of mathematical Sciences, 2007),

$$g\int_0^{H_{stat}} \rho_{stat}(x)dx = P_{stat}(H_{stat})\text{-}P_{stat}(0) \tag{5}$$

$$g\int_0^{H_{dyna}} \rho_{dyna}(x)dx = P_{dyna}(H_{dyna})\text{-}P_{dyna}(0) \tag{6}$$

It can be seen from the equation (1) that the atmospheric pressure P_{atm} acting on the liquid level of wellbore is the same, and the gravitational acceleration g is also the same and head lost during the movement of the geothermal fluid P_{lose} is greater than zero. At the same time, if surface tension of liquid surface is ignored, the hydrostatic pressure P_{stat} and dynamic water pressure P_{dyna} generated at the liquid level in the well water column are equal to zero.

It can be seen from equations (5) and (6) that in a cold water well, since the temperature change is small, the density of water in the well is also small, so there is generally $\rho_{stat}(x) = \rho_{dyna}(x) = \rho$ (*ρ* is constant), then

$$P_{stat}(x) = P_{dyna}(x) = \rho x \tag{7}$$

$$P_{stat}(H_{stat})=\rho H_{stat} \quad (8)$$

$$P_{dyna}(H_{dyna})=\rho H_{dyna} \quad (9)$$

If $\rho H_{stat} > \rho H_{dyna}$, then, the static water level is higher than the moving water level, which is the most common phenomenon in cold water wells.

In geothermal wells, temperature of geothermal fluid in the well varies greatly, so density of geothermal fluid also changes greatly. Since $\rho_{stat}(x)$ and $\rho_{dyna}(x)$ are variables, their values also change with temperature of geothermal fluid. Therefore, under hydrostatic conditions and pumping conditions, there are two possibilities for water level in geothermal wells, namely $H_{stat} > H_{dyna}$ or $H_{stat} < H_{dyna}$. This is the reason why dynamic water level in the well is sometimes higher than static water level and sometimes lower than static water level. According to equation (5) and equation (6), under hydrostatic and pumping conditions, only dynamic water level and static water level are obtained, and pressure of geothermal well bottom cannot be calculated. It is also necessary to obtain density functions $\rho_{stat}(x)$ and $\rho_{dyna}(x)$ of the geothermal fluid.

The density of water is generally affected by pressure and temperature. According to the research of Zhang et al. (2010) and Xue et al. (2005), in the low-speed flow state of geothermal well pumping, it can be considered that geothermal fluid is an incompressible fluid, that is, the influence of pressure on the liquid density is negligible.

However, under the influence of temperature, the geothermal fluid has a relatively large range of density variation, which has a great influence on the calculation of well bottom pressure. According to the geothermal resource geological exploration specification (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration, 2011), the relationship between density and temperature can be expressed as (Fig. 2),

$$\rho(t) = -0.0036t^2 - 0.0734t + 1000.7 \quad (10)$$

For the convenience of calculation, you can use a, b, c instead of the coefficient and constant term of the variable. So formula (10) can be written in the following form,

$$\rho(t) = at^2 + bt + c \quad (11)$$

3. AVERAGE DENSITY METHOD

When well temperature and well depth show a good linear relationship, Zhou et al. (2000) used average density of wellhead and bottom of well to calculate the bottom hole pressure. The calculation formula is as follows,

$$\begin{aligned} P_{stat-bottom} &= P_{stat} + P_{atm} = \rho_{stat-ave} g H_{stat} + P_{atm} \\ &= \frac{1}{2}(\rho_{stat-head} + \rho_{stat-bottom}) g H_{stat} + P_{atm} \end{aligned} \quad (12)$$

$$\begin{aligned} P_{dyna-bottom} &= P_{dyna} + P_{atm} = \rho_{dyna-ave} g H_{dyna} + P_{atm} \\ &= \frac{1}{2}(\rho_{dyna-head} + \rho_{dyna-bottom}) g H_{dyna} + P_{atm} \end{aligned} \quad (13)$$

$$P_{drop} = P_{stat} - P_{dyna} \quad (14)$$

Where $\rho_{stat-ave}$, $\rho_{stat-head}$, $\rho_{stat-bottom}$, $\rho_{dyna-ave}$, $\rho_{dyna-head}$, $\rho_{dyna-bottom}$ are average density from wellhead to bottom of well in hydrostatic conditions, density of wellhead under hydrostatic conditions, density of well bottom under hydrostatic conditions, average density from wellhead to bottom of well under pumping conditions, density of wellhead under pumping conditions and density of well bottom under puming conditions, respectively.

4. SEGMENTATION METHOD

When temperature in the well exhibits a multi-segment linear relationship, the calculation using average density method is inaccurate. The well can be divided into several sections according to the well temperature characteristics for calculation. Each section has better linear characteristics. Finally, the calculation results of all the well sections are summed to obtain the total well bottom pressure.

The density of geothermal fluid in the well is calculated according to equation (10). The pressure value of each section is calculated from the average density of top and bottom of the water column as the density of whole section. The pressure value generated by each section of the water column is

$$P_i = \frac{(\rho_{i-1} + \rho_i)}{2} g h_i \quad (15)$$

The well bottom pressure is,

$$P_{\text{stat}-bottom} = P_{stat} + P_{atm} = \sum_{i=1}^{n} \frac{(\rho_{(i-1)stat} + \rho_{(i)stat})}{2} gh_{(i)stat} + P_{atm} \quad (n = 31) \tag{16}$$

$$P_{dyna-bottom} = P_{dyna} + P_{atm} = \sum_{i=1}^{n} \frac{(\rho_{(i-1)dyna} + \rho_{(i)dyna})}{2} gh_{(i)dyna} + P_{atm} \quad (n = 31) \tag{17}$$

5. CASE STUDY

5.1 Integral Method Calculation

The measured down-hole data of geothermal wells in Beijing revealing the karst geothermal reservoir showed that the change of down-hole temperature is divided into two sections (Fig. 3). The first section is from the wellhead to the 1100m section. The relationship between well temperature and depth can be expressed as,

$$t(x) = 0.0328x + 21.941 \tag{18}$$

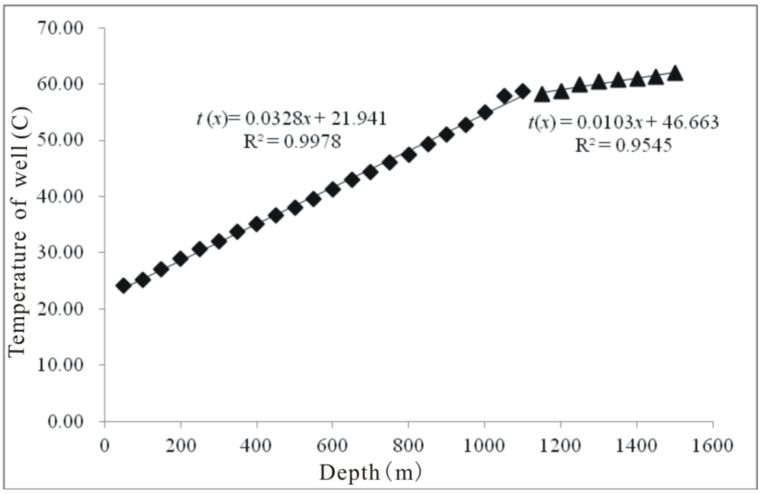

Figure 3: Relationship between geothermal well temperature and depth under static condition

As with the equation (10), the variable coefficients and constant terms in the equation (12) can be replaced by d_1 and e_1. Therefore, equation (12) can be written in the following form,

$$t(x) = d_1 x + e_1 \tag{19}$$

where：d_1=0.00328，e_1=21.941.

The second section is 1100-1500m. The relationship between well temperature and depth can be expressed as,

$$t(x) = 0.0103x + 46.663 \tag{20}$$

As with the equation (10), the variable coefficients and constant terms in the equation (14) can be replaced by d2 and e2. Therefore, equation (14) can be written in the following form,

$$t(x) = d_2 x + e_2 \tag{21}$$

where：d_2=0.0103，e_2=46.663.

Substituting equations (13) and (15) into equation (10) and combining the same terms and obtain following equations,

$$\rho_1(x) = ad_1^{\,2}x^2 + (2ad_1e_1 + bd_1)x + ae_1^{\,2} + be_1 + c \tag{22}$$

$$\rho_2(x) = ad_2^{\,2}x^2 + (2ad_2e_2 + bd_2)x + ae_2^{\,2} + be_2 + c \tag{23}$$

According to equation (1) and equation (2), under hydrostatic conditions, the pressure generated by the water column in the well to the bottom of well is,

$$
\begin{aligned}
P_{stat} &= \int_0^{H_{stat}} \rho(\mathrm{x}) g dx = g\int_0^{H_{stat}} \rho(\mathrm{x}) dx \\
&= g\int_0^{H_{stat}} (ad^2x^2 + (2ade+bd)x + ae^2 + be + c)dx \\
&= g[\frac{1}{3}ad^2x^3 + \frac{1}{2}(2ade+bd)x^2 + (ae^2+be+c)x]_0^{H_{stat}} \\
&= g[\frac{1}{3}ad_1{}^2x^3 + \frac{1}{2}(2ad_1e_1+bd_1)x^2 + (ae_1{}^2+be_1+c)x]_0^{1100-h} \\
&+ g[\frac{1}{3}ad_2{}^2x^3 + \frac{1}{2}(2ad_2e_2+bd_2)x^2 + (ae_2{}^2+be_2+c)x]_{1100-h}^{H_{stat}}
\end{aligned} \tag{24}
$$

If the atmospheric pressure P_{atm} on the liquid surface is taken into account, the well bottom pressure is $P_{stat\text{-}bottom} = P_{stat} + P_{atm}$.

Under pumping conditions, the geothermal fluid with a higher temperature in the well continues to move toward wellhead. Due to higher temperature of geothermal fluid, the well wall can be heated in a short time. In this process, the geothermal fluid loses a certain amount of thermal energy. Since heat transfer between well wall and formation is dominated by conduction, the transfer speed is very low. In the case of continuous pumping, the heat loss of geothermal fluid will be less and less. In this case, it can be assumed that temperature of the geothermal fluid in the well is linear with depth (Fig. 4), which can be expressed as follows,

$$t(x) = 0.0014x + 59.891 \tag{25}$$

As with the equation (10), the variable coefficients and constant terms in the equation (25) can be replaced by d_1 and e_1. Therefore, equation (25) can be written in the following form,

$$t(x) = dx + e \tag{26}$$

where：d=0.0014，e=59.891.

Under pumping conditions, the pressure generated by the water column in the well bottom is,

$$
\begin{aligned}
P_{dyna} &= \int_0^{H_{dyna}} \rho(\mathrm{x}) g dx = g\int_0^{H_{dyna}} \rho(\mathrm{x}) dx \\
&= g\int_0^{H_{dyna}} (ad^2x^2 + (2ade+bd)x + ae^2 + be + c)dx \\
&= g[\frac{1}{3}ad^2x^3 + \frac{1}{2}(2ade+bd)x^2 + (ae^2+be+c)x]_0^{H_{dyna}} \\
&= g[\frac{1}{3}ad^2x^3 + \frac{1}{2}(2ade+bd)x^2 + (ae^2+be+c)x]_0^{H_{dyna}}
\end{aligned} \tag{27}
$$

If the atmospheric pressure P_{atm} on the surface is considered, the bottom pressure is $P_{dyna\text{-}bottom} = P_{dyna} + P_{atm}$. Therefore, the pressure drop caused by pumping is,

$$P_{drop} = P_{stat} - P_{dyna} \tag{28}$$

The above-mentioned geothermal well has a buried water head depth of 83.5 m before pumping, and a dynamic water head depth of 79.5 m when pumping is stable, which cannot be directly used to calculate permeability of the geothermal reservoir. Therefore, it is necessary to first calculate pressure drop caused by pumping, and the results are as follows (Table 1),

$$P_{drop} = P_{stat} - P_{dyna} = 13850548.81 - 13793246.98 = 57301.83\,Pa \tag{29}$$

5.2 Average Density Method

The bottom pressure calculated by average density method is shown in Table 1.

$$P_{drop} = P_{stat} - P_{dyna} = 13863643.97 - 13792659.66 = 70984.31\,Pa \tag{30}$$

5.3 Segmentation Method

According to actual down-hole temperature logging and well test results, the average temperature increase rate per 50m under hydrostatic conditions is 0.16 °C, and the average density change rate is 0.08 kg/m^3. The average temperature increase rate per 50m under pumping conditions is 1.31 °C, and the average density change rate is 0.51 kg/m^3. Therefore, geothermal wells can be segmented at intervals of 50 m. For the convenience of calculation, divide the liquid level to 79.5m into the first section, divide

79.5 to 83.5m into the second section, divide 83.5 to 100m into the third section, and divide the 100 to 1500m into the fourth section to the 31st section.

The pressure drop caused by pumping is (Table 1),

$$P_{drop} = P_{stat} - P_{dyna} = 13839009.31 - 13792445.70 = 46563.61\ Pa \quad (31)$$

Table 1： Calculating results of geothermal well bottom pressure

Methods		P_{stat} (Pa)	P_{dyna} (Pa)	P_{drop} (Pa)	Converted to water column height （m）
Calculated results	Integral method	13850548.81	13793246.98	57301.83	5.66
	Average density method	13863643.97	13792659.66	70984.31	7.01
	Segmentation method	13839009.31	13792445.70	46563.61	4.60

6. RESULTS AND DISCUSSION

6.1 Relationship between Hydrodynamic Pressure and Hydrostatic Pressure

Although the calculation results of integration method, average density method, and segmentation method are different, all the results showed that hydrostatic pressure at the bottom of geothermal well is greater than hydrodynamic pressure, even when hydrodynamic water level is higher than static water level. This is because pumping process discharges geothermal fluid in the geothermal reservoir, reducing pressure of geothermal reservoir, resulting in hydrodynamic pressure being less than hydrostatic pressure.

6.2 Accuracy of Calculated Results

Considering that temperature of geothermal fluid in the well is continuous, the density is also continuous. It is most reasonable and accurate to calculate bottom pressure by integral method.

If temperature of geothermal fluid in geothermal well exhibits a very good linear relationship with well depth, average density method can be used to approximate bottom pressure, and the accuracy of calculation result is worse than integral method. If well temperature and well depth exhibit a nonlinear relationship, the application of average density method will have a large deviation, and it will not reflect real situation in well.

The segmentation method can be said to be further refined by average density method, that is, geothermal fluid in the well is divided into several separately for calculation and addition. Therefore, the segmentation method has a much higher precision than average density method. On the other hand, segmentation method actually reflects idea of integral method. If interval segmentation in the calculation process is small enough, the calculation result can infinitely approximate the calculation result of the integral method.

6.3 Applicability of Calculation Method

If the relationship between temperature and depth of geothermal fluid in the well can be accurately known and can be accurately expressed by the relationship, calculation result of integral method is the most reasonable and the most accurate method. It should be emphasized here that if relationship between temperature of geothermal fluid in the well and depth of the well is complicated, it is necessary to describe relationship between well temperature and depth of the well in sections, and obtain relationship between fluid temperature and well depth as much as possible, and then integrate.

When temperature distribution of geothermal fluid in well shows a very good linear relationship with well depth, the average density method can also be used to calculate the results similar to integral method and segmentation method. But in general, average density method is the simplest calculation process, but the calculation results have the largest error.

Compared with the above two methods, segmentation method has the strongest applicability. Even if temperature distribution of fluid in the well is very irregular, and it is difficult to express it with a simple relationship, as long as the interval is sufficiently thin, the calculation result will be closer to actual situation.

7. CONCLUSIONS AND EXPECTATIONS

7.1 Conclustions

In order to accurately calculate production capacity of geothermal wells and parameters of geothermal reservoir, especially when dynamic water level is higher than static water level, it is necessary to first calculate hydrostatic conditions and pressure of geothermal well bottom under pumping conditions. When calculating bottom pressure, the two most important parameters are the static (dynamic) water level and the geothermal fluid density. The calculation results shown that whether static water level of geothermal well is higher than dynamic water level or lower than dynamic water level, hydrostatic pressure at the bottom of well before pumping is greater than hydrostatic pressure at bottom of well. This also theoretically proves that it is more reasonable and more accurate to use geothermal well bottom hydrostatic and hydrodynamic pressure difference to calculate geothermal reservoir parameters than water level difference.

In this paper, bottom pressure is calculated by three methods. Density function involved in integral method theoretically explains density distribution characteristics of geothermal fluids. It is the most reasonable and most accurate method for calculating geothermal well bottom pressure, and the preferred method for calculating geothermal well bottom pressure. Segmentation method has lower requirements on data. If calculation interval is sufficiently thin, calculation result is closer to the actual situation, which is equivalent to numerical solution of bottom pressure. If geothermal fluid temperature distribution exhibits a very good linear relationship with well depth, geothermal bottom pressure can also be calculated using average density method approximation. The accuracy of calculation results of these three methods is affected by the accuracy of temperature measurement in the well on the one hand, and by the accuracy of the relationship between temperature of geothermal fluid and depth of well on the other hand.

7.2 Expectations

At present, geothermal development process pays great attention to the distribution of temperature in geothermal wells than pressure distribution. Therefore, after completion of well, only temperature measurement is generally performed and measurement of the down-hole pressure distribution is rarely performed. This makes pressure calculation result unable to be corrected by measured data, so that the accuracy of calculation results cannot be determined. Therefore, if well temperature and pressure can be measured simultaneously in the future logging process, it will provide very good correction data for calculation of pressure, and will also provide a basis for improvement of calculation method.

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