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Temperature Distribution Modeling in Geothermal Wellbore and Formation During the Well Test in Yangyi Geothermal Field, Tibet

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ABSTRACT

The physical property and rheological behavior parameters of fluid in the wellbore are sensible functions of temperature, exact calculation of temperature distribution is fundamental to predict the wellbore pressure distribution, proceed optimization procedure and analyze of its behavior. The formation temperature calculated by single geothermal gradient can hardly describe the initial formation temperature(INF) because of the different thermophysical properties in formation and reservoir. This paper calculated the initial formation temperature by Honer Method, analyzed heat transfer process in wellbore and formation, considered the convection effect of groundwater in the aquifer, established a mathematical model which included steady-state heat transfer in the wellbore and unsteady-state heat conduction in the formation. According on the model, ZK212 in Yangyi Geothermal Field ,Tibet, was taken as an example to calculate the fluid temperature in the wellbore, simulated the sensitivity analysis by assumed parameters, such as well diameter, outflow, thermal conductivity of cement, impacted on the wellhead temperature, and optimized the wellhead temperature.

1. INTRODUCTION

Temperature is an indispensable indicator to evaluate productivity of geothermal wells, and affects the stability of the surrounding rock. Fluid temperature is continuously change when the fluid flows up to the surface, because the temperature difference between fluid and surrounding rock lead to heat transfer (conduction, convection and radiation). Temperature logging is the direct approach to achieve the fluid temperature in the wellbore, however, the method records a couple of intermittent and transitory data and incomplete information in spite of the intense enhancement on logging equipment. Ben Dhia emphasized that the accurate temperature of initial formation and fluid can't be measured by any single temperature logging. The main approach to research the fluid temperature distribution in wellbore is to establish model, which includes the equations of mathematical physics and numerical model, then calculates the exact results and analyses the each parameter (flow rate, borehole diameter, time and geological properties) impacting on the distribution of fluid temperature.

The research on the issue has continued for 50 years. Ramey (Ramey, 1962) proposed the model which modeled the heat transfer process in hot-water-injection wells, which was built on condition that heat transfer in the well was stable and heat transfer in formation is transient heat radiation. Ramey model was modified and developed later, Sagar (Sagar et, al, 1991) expanded Ramey Model into multiphase flow system added the kinetic energy variation and Joule-Thompson effect. Hagoort and Assocs (Hagoort and Assocs, 2004) presented a simple graphical correlation to revise Ramey Model can estimate temperature the length of early transient period. Satter (Satter, 1967) model investigated the influence of gas phase variation in steam-injection well. Willhite (Willhite, 1969) deduced the computational methods of the overall heat transfer coefficient and natural-convection flow in annulus. Hasan and Kabir (Hasan and Kabir, 1994c) established one-dimension pseudo-steady state model and calculated the analytic solution. Hasan and Kabir (Hasan and Kabir, 2010) built two-phase flow model of geothermal well which considered heat loss. Zhou (Zhou, 2010) assessed the heat transfer in an aquifer utilizing fractal theory. Wang (Wang, 2013)inferred wellbore temperature field control equations based on the conservation of energy during the drilling fluid circulation and took account of the stable heat transfer in wellbore and transient transfer between wellbore and formation.

Raymond (Raymond, 1969) researched numerical method about the drilling fluid circulation temperature ignoring heat source in the well. Keller et, al (Keller et al, 1973) expanded the one-dimension drilling circulation temperature numerical model into two-dimension with ignoring the radial heat transfer of drilling fluid, and applied finite-difference method to compute. Marshall and Bentsen (Marshall and Bentsen, 1982) improved the Keller Model and calculated the result by finite-difference method under the stable flow rate. Wang and Li (Wang and Li,1993) improved the former numerical calculation method, proposed an astable heat transfer numerical calculation method and software under consideration of heat transfer between the initial fluid with wellbore, cement and formation. Romero and Toboul (Romero and Toboul, 1998) calculated the numerical solution of three-dimension astable heat transfer model after researching wellbore temperature distribution in deep water offshore drilling.

Geothermal gradient is generally served to calculate the formation temperature of traditional wellbore temperature distribution model. However, because of the specificity of geothermal well, the formation temperature calculated by the geothermal gradient exists intensely error compared with the actual formation temperature, which leads to serious simulation error. Thus, precise formation temperature should be known before researching the temperature distribution in geothermal wellbore.

2. INITIAL FORMATION TEMPERATURE MODEL

Formation temperature is a crucial thermal physics parameter to research the heat transfer process in geothermal well. Formation temperature is measured when existed heat balance between formation and annulus medium after the drilling process or well completion. Because of long thermal recovery time and low instrument precision, the formation temperature can hardly be measured directly and is generally replaced by static formation temperature.

2.1 Horner Method

Horner Method suggested thermal balance calculation formula under the assumption that the borehole is a linear heat source, and further calculated the time which the formation recovered heat balance.

Some assumption should be paid before using Horner Method for (1) wellbore is an infinitely long cylinder and the formation out of the wellbore is infinitely distribution as well, (2) there is none heat source and same thermal diffusivity existed inside and outside the wellbore, (3) only radial heat source is considered in the wellbore.

Downhole temperature variation law follows the non-Steady heat conduction differential equations as below (Hagoort, 2004).

$$\frac{\partial^2 T}{\partial^2 r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{C_f \rho_f}{\lambda_f}\frac{\partial T}{\partial t} \tag{1}$$

where, T is the measured formation temperature after stop drilling and circulation, °C; t is time, h; r is the distance from the wellbore center, m; C_f is formation thermal capacity, J/(kg°C); ρ_f is density of formation, kg/m^3; λ_f is thermal conductivity of formation, W/(m·K).

When solving equations, the relation of wellbore temperature and logarithm of time can be counted as an approximate linear on considering that actual wellbore temperature is measured after stop drilling and drilling fluid circulation for a short time.

$$T = K\,log\left(1+\frac{T_k}{\Delta T}\right)+T_f \tag{2}$$

Where, T_f is the initial formation temperature,°C; T_k is wellbore cooling temperature, h; ΔT is the time interval between measure time and time of stop drilling and drilling fluid circulation, h; K is scale factor.

3. MATHEMATICAL MODEL OF WELLBORE TEMPERATURE FIELD

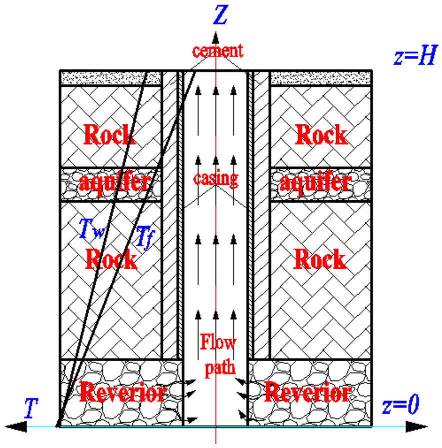

Figure 1: wellbore structure and temperature distribution model during test, T_w is the fluid temperature in the wellbore, T_f is the initial formation temperature.

As showed in Fig. 1, thermal fluid in reservoir flows into the wellbore at the point of $z=0$, $T_w|_{z=0}=T_f|_{z=0}$. Convection heat transfer occurs between the thermal fluid and formation during the fluid rises process, and up to the surface at the point of $z=H$.

While constructing the wellbore temperature field model, a few assumptions should be listed (1) the Joule-Thompson Effect of fluid in wellbore is neglected, (2) it is homogeneous for rock in each formation layer, borehole diameter doesn't change with the depth, (3) the influence of frictional heat is neglected, (4) the phase of the fluid in the wellbore doesn't transform.

3.1.1 the model of heat transfer from the formation to the wellbore

In the process of thermal fluid rising, temperature difference between the wellbore fluid and the surrounding formation results of energy exchange. A small section of wellbore dz is selected as the research object. Energy flow is showed in Fig.2

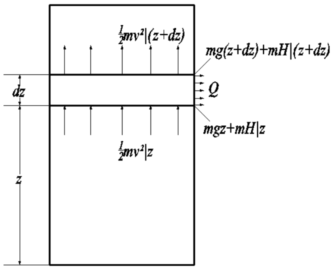

Figure 2: Energy flow of element *dz* in annulus.

According to the conservation of energy theory, the energy of the element *dz* in the annulus is given (Zhou, 2015)

$$-mgz + mH\big|_z + \frac{1}{2}mv^2\bigg|_z = -mg(z+dz) + mH\big|_{z+dz} + \frac{1}{2}mv^2\bigg|_{z+dz} + Q \tag{3}$$

Where, m is mass flow of fluid, kg/s; z is the depth, m; H is fluid enthalpy, J/kg; v is the velocity of the fluid, m/s; Q is the energy transfers from fluid to surrounding formation, J.

Eq. 3 can be simplified as :

$$-gz + H\big|_z + \frac{1}{2}v^2\bigg|_z = -g(z+dz) + H\big|_{z+dz} + \frac{1}{2}v^2\bigg|_{z+dz} + \frac{Q}{m} \tag{4}$$

$$\frac{dH}{dz} - gdz + \frac{vdv}{dz} + \frac{Q}{m} = 0 \tag{5}$$

Q is the energy transfers from fluid in surrounding formation,can be expressed as:

$$Q = 2\pi r_0 U(T_w - T_{if}) \tag{6}$$

H is the enthalpy of fluid in the wellbore, as the Joule-Thompson effect is taken no account in this study, it can be expressed as the function of temperature

$$dH = (\frac{\partial H}{\partial T})_p dT = c_p dT \tag{7}$$

Using Eq. 7, the energy conservation equation can be written as a function of fluid temperature in the wellbore.

$$\frac{dT_w}{dz} = \frac{1}{c_p}(-\frac{Q}{m} + g\sin\theta - \frac{\upsilon d\upsilon}{dz}) \tag{8}$$

Where, r_0 is radius of the inner casing ,m; U is the overall heat transfer coefficient, W/(m·K); T_w is fluid temperature in wellbore, ℃; T_{if} is the interface temperature between formation and wellbore,℃.

Heat will transfer through casing and cement and energy transfers from fluid into formation, consequently, the overall heat transfer coefficient can expressed as (Zhou, 2013):

$$U = \frac{1}{(R_f + R_c + R_t)} / r_0 \tag{9}$$

The convection resistance of heat flow near the inner tubing R_f is

$$R_f = \frac{1}{2\pi h_f r_0} \tag{10}$$

Where, r_0 is the radius of inner casing, m, h_f is the convection heat transfer coefficient of casing, W/(m^2·K).

The conduction resistance of casing R_c,

$$R_c = \frac{ln(r_1 / r_0)}{2\pi\lambda_c} \tag{11}$$

Where, r_1 is the radius of outer casing, m, λ_c is thermal conductivity of casing, W/(m·K).

The conduction resistance of cement R_t,

$$R_t = \frac{ln(r_2 / r_1)}{2\pi\lambda_t} \tag{12}$$

Where, r_2 is the radius of cement, m; λ_t is thermal conductivity of cement, W/(m·K).

Combine equations (7), (8) and equation (9), Eq. 6 can be expressed as,

$$U = \frac{1}{r_0(\frac{1}{2\pi h_f r_0} + \frac{ln(r_1 / r_0)}{2\pi\lambda_c} + \frac{ln(r_2 / r_1)}{2\pi\lambda_t})} \tag{13}$$

Where, L_R is the relaxation parameter.

3.1.2 Aquifer temperature control equations

Under the condition that fluid operates in one-dimensional radial flow mode in porous media and the energy produced by aquifer pressure work and mechanical energy loss during the flow are neglected, based on the energy equation of porous media, aquifer temperature control equation can be written as follow (Shi, 2004),

$$(\rho c)^* \frac{\partial T}{\partial t} = -\rho c \upsilon \, \overrightarrow{gradT} + div(\lambda^* \overrightarrow{gradT}) \tag{14}$$

$$(\rho c)^* = (1-\varphi)(\rho_r c_r) + \varphi(\rho_l c_l) \tag{15}$$

$$\lambda^* = \lambda_r^{\varphi} * \lambda_l^{(1-\varphi)} \tag{16}$$

Where, $(\rho c)^*$ is the equivalent specific heat capacity of aquifer rock, J/(m^3·°C); υ is the seepage velocity, m/s; φ is porosity; ρ_r is density of rock, kg/m^3; c_r is heat capacity of rock, J/(kg·°C); ρ_l is density of fluid, kg/m^3; c_l is heat capacity of fluid, J/(kg·°C); λ^* *is* equivalent thermal conductivity of aquifer, W/(m·K); λ_r *is* thermal conductivity of rock, W/(m·K); λ_l *is* equivalent thermal conductivity of fluid, W/(m·K).

As the shallow aquifer is insulated by the cement and casing, so we can consider the fluid in aquifer is relatively static, i.e. $\upsilon = 0$, the heat transfer in the shallow aquifer is heat conduction.

$$(\rho c)^* \frac{\partial T}{\partial t} = div(\lambda^* \overrightarrow{gradT}) \tag{17}$$

3.2 Initial and Boundary Conditions

3.2.1 Initial condition

The initial temperatures of formation and wellbore are those in statics conditions,so the initial condition is,

$$T(z) = K \log\left(1 + \frac{t_k}{\Delta t}\right) + T_f \tag{18}$$

The wellbore temperature and the formation temperature should be equal at the depth ofbottom hole,

$$T_w\big|_{z=L} = T_f\big|_{z=L} \tag{19}$$

3.2.2 Boundary conditions of wellbore

Assumption the top of the wellbore is insulation,

$$\lambda_l \frac{\partial T}{\partial z}\bigg|_{z=L;r\le r_1} = 0 \tag{20}$$

Where, L is the depth of bottom hole, m; λ_l is the thermal conductivity of fluid in the wellbore, W/(m·K).

Assumption the bottom of the wellbore is insulation,

$$\lambda_l \left.\frac{\partial T}{\partial z}\right|_{z=0;r\leq r_l} = 0 \tag{21}$$

3.3.2 Boundary conditions of formation

Assumption the top of the formation is insulation,

$$\lambda \left.\frac{\partial T}{\partial z}\right|_{z=L;r\geq r_l} = 0 \tag{22}$$

Assumption the bottom of the formation is insulation,

$$\lambda \left.\frac{\partial T}{\partial z}\right|_{z=0;r\geq r_l} = 0 \tag{23}$$

Because of a condition for the fluid temperature in the wellbore not influencing the infinite formation, the formation temperature hardly affected by the fluid temperature,

$$T\Big|_{r>>r_l} = K\,log\left(1 + \frac{t_k}{\Delta t}\right) + T_f \tag{24}$$

Wellbore and formation coupling boundary conditions, the heat flows out the formation should be equal to the heat transfers into the annulus.

$$\left[h + \frac{2\pi\lambda_c\lambda_t}{\lambda_t ln(r_2/r_1) + \lambda_c ln(r_1/r_0)}\right](T_w - T_{if}) = \lambda_f \left.\frac{\partial T}{\partial r}\right|_{r=r_2} \tag{25}$$

4. CALCULATION AND ANALYSIS

ZK212 in Yangyi Geothermal Field is selected as the test well to calculate, the vertical depth of the well is 1508 and the measured bottom temperature is 210℃. The rock of the formation is mainly porphyritic granite.

Different materials have different properties of thermodynamics, the thermodynamics properties of materials and formation are listed in Table 1.

Table 1: thermodynamics properties of materials and formation.

Formation and materials	Density (kg/m^3)	Thermal conductivity (W/(m·K))	Thermal capacity (J/(kg·℃))
Sandstone	2231	1.869	711.76
Basalt	1579	2.008	879.23
Granite	2641	2.821	837.36
Cement	2100	1.454	879.23
Casing	7848	45.174	460.55

4.1 Initial formation temperature

The last circulation of the drilling fluid lasted 21h and ended at 11:40 in June 28, 2013. Twice logging were conducted at 8:24 and 16:12 in June 29, 2013 respectively. According to the twice temperature-depth measure, we calculated the initial formation temperature by Horner Method.

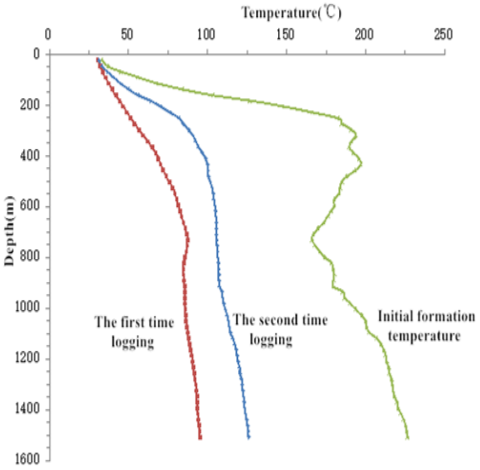

Figure 3: Measured wellbore temperatures and initial formation temperature calculated by Horner Method.

As shown in Fig. 3, the geothermal gradients can be divided into three section in the well, upper geothermal gradient which is from surface to 400m, has a large slope, which indicted the formation is cap rock. The formation temperature reversed from 400m to 800m, which is the feature of runoff, so the thermal water in shallow reservoir act runoff. And the temperature resumes elevates til the bottom hole and up to 210 ℃.

4.2 Temperature distribution in wellbore

According to the parameter of wellbore and formation, the distribution of fluid temperature are shown in Fig. 4.

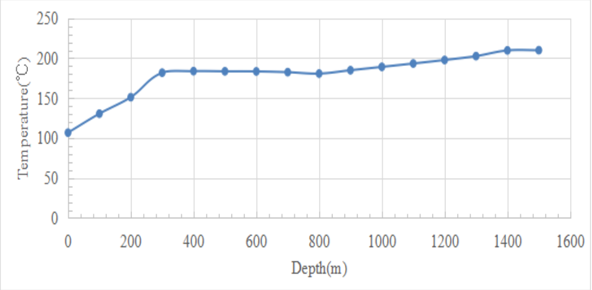

Figure 4: the wellbore temperature with the depth.

The main effect factors on fluid temperature are determined on basis of the parameter used in the calculation, the main factors are: test time; mass flow rate; diameter of wellbore and thermal conductivity of cement.

4.2.1 Test time

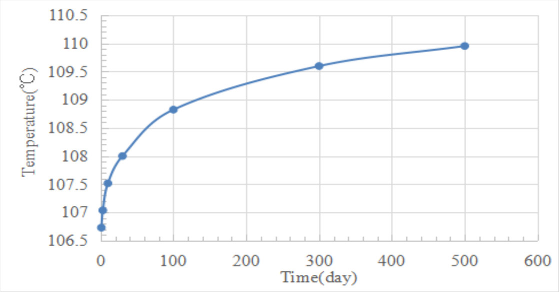

Figure 5: wellhead temperature with the test time.

As shown in Fig. 5, the temperature of wellbore increase with time, but the rate of rise diminished continuously.,and the increase of temperature is less than 1℃/100day, we can consider that the temperature in the wellbore is stable.

4.2.2 Flow rate

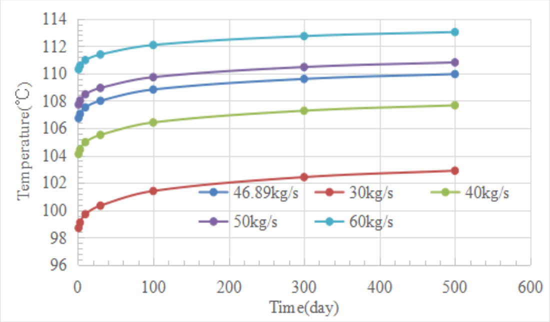

Figure 6: wellhead temperature with mass flow rate.

Mass fluid rate is a crucial parameter to the wellhead temperature. As illustrated in Fig.6 Mass flow rate change leads to huge difference of wellhead temperature, and the unstable time is shorter and shorter. However, the growth rate of temperature is gradually slow, so the wellhead temperature would independent on mass flow rate at some point, and huge fluid rate is limited by the reservoir and the pressure of wellhead or power of pump, the optimized fluid rate will be selected according to the situation of well and the condition of the whole project.

4.2.3 Diameter of wellbore

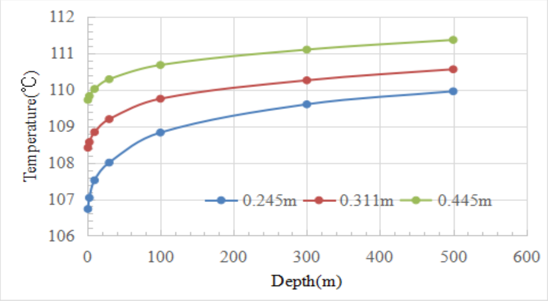

Figure 7: wellhead temperature with the diameter of wellbore.

The Fig. 7 implies that wellhead temperature still increases following the size of wellbore, while the change of the temperature with wellbore geometry is not very large .

4.2.4 Thermal conductivity of cement

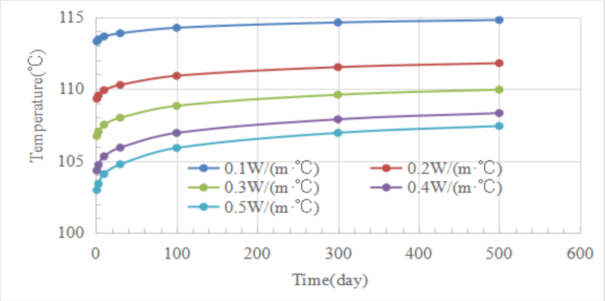

Figure 8: wellhead temperature with the thermal conductivity of cement.

Fig. 8 illustrates low thermal conductivity of cement, the space between casing and formation becomes an important isolated area for heat flow, while the cement with low conductivity also has week performance on other properties like strength.

5. CONCLUSION

The paper focuses on the test process of open system in deep geothermal energy. As the geothermal gradient is not singular in the geothermal wells, so the actual formation temperature must be clear before modeling.

Actual formation temperature of ZK212 in Yangyi Geothermal Field was calculated, three geothermal gradients exsited in the well, and the formation temperature reversed from 400m to 600m, which is the feature of runoff, so the thermal water in shallow reservoir act runoff.

A mathematical model which reflected the heat transfer process of the system was established. ZK212 in Yangyi Geothermal Field, Tibet was selected to realize the model and a simulation of sensitivity analysis also completed . The result showed that thermal conductivity of cement and mass flow rate are the main factors to guarantee stable wellhead temperature.

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