Numerical Simulation of Wellbore Temperature for Multi-Geothermal Gradients in Guide ZR_1 Geothermal Well, Qinghai, China

Duan Chenyang[1], Zheng Xiuhua[1], Wang Zhiqing[1], Xu Qi[2]

[1] China University of Geosciences, Beijing, Beijing, China

[2] Geological Exploration Institute of Shandong Zhengyuan, Shandong, China

Keywords

Wellbore temperature; model; Multi-geothermal Gradients

ABSTRACT

Temperature is a crucial parameter for geothermal drilling. The accurate wellbore temperature can prevent blowout and fracturing formation and ensure the safe drilling. To obtain precise wellbore temperature distribution during the circulation, a wellbore temperature model was developed to account for the transient heat exchange process based on energy exchange mechanisms of wellbore and formation systems during circulation. ZR_1 geothermal well was taken as an example to test the model by COMSOL. The result showed that the model is fit for the actual situation; the error was mainly from the inaccurate parameter. The wellbore temperature decreased with the time, and finally stable. The temperature model which used constant geothermal gradient would easily bring big errors especially high temperature geothermal well. The model adopted multi-geothermal gradients which followed the initial formation temperature can calculate wellbore temperature accuracy.

1. Introduction

In recent years, renewable energy is being paid more and more attention to all countries due to their characteristics of low-pollution. Geothermal energy, as one of the renewable energy, is in fast-growing period (Xu, 2014). Compared with the other renewable energy, the cost on initial investment (exploration, production and injection of geothermal wells) constitutes major component cost of geothermal projects (Zheng, 2016). Therefore, how to safe and fast drilling is the main subject in geothermal development.

The accurate wellbore temperature not only determines the density and rheology of drilling fluid, but also prevents lost circulation/blowout and fracturing formation (Liu, et al, 1996; Wei, et al, 2004).

Measure the wellbore temperature directly is difficult and extremely uneconomic. 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 (Duan, 2016). The heat transfer model of wellbore and formation has been studied for several years, Ramey (1962) proposed the model which modeled the heat transfer process in hot-water-injection wells. The model just had good compatibility to heat transfer process in the stable state, while large error might be produced in transient state. In subsequent studies, scholars developed and improved the Ramey Model and built the steady heat transfer model (Holmes et al., 1970; Hasan et al., 1996, 2009, 2010) and transient heat transfer model (Raymond, 1969; Keller et al., 1973; Espinosa-Paredes et al., 2001; Yang et al, 2013a, b; Wu et al, 2014) to analyze the wellbore temperature.

In the conventional models, the geothermal gradient is considered constant in the whole well, while the multi-geothermal gradients exist in the wells as several reservoirs and cap rocks coexist in one geothermal system. The geothermal gradient in cap rock is much larger than that in reservoir, so the calculated wellbore temperature would deviate the actual temperature distribution.

This paper built the wellbore temperature distribution model based on the conservation of energy theorem and heat transfer theory, evaluated the accuracy of the model during circulation, determined the main error sources and calculated the annular temperature with multi-geothermal gradient and constant geothermal gradient which indicated the annular temperature with constant geothermal gradient would lead to cause a relatively big error and give rise to danger.

2. Wellbore heat transfer model in drilling fluid circulation

Some assumptions should be paid before building the model to simplify wellbore condition: (1) convection in formations should be neglected; (2) the density, thermal properties and rheology of drilling fluid are independent of temperature; (3) the density and thermal properties of pipes, cement and formation perform isotropy; (4) axial heat conduction can be ignored; (5) the influence of inner heat source can be considered non-existent and (6) the heat convention in formation is overlooked .

As shown in Figure 1, the drilling fluid flows into the pipes and then enters the annulus and finally back to the surface. According to the conservation of energy, the temperature-governing equations in the wellbore and formation can be listed as Eq. 1.

$$\begin{cases} \rho_1 c_1\left(\frac{\partial T_1}{\partial t}+v_1 \nabla T_1\right)=k_1\left(\frac{1}{r}\frac{\partial T_1}{\partial r}+\frac{\partial^2 T_1}{\partial r^2}+\frac{\partial^2 T_1}{\partial z^2}\right) \\ \rho_2 c_2\frac{\partial T_2}{\partial t}=k_2\left(\frac{1}{r}\frac{\partial T_2}{\partial r}+\frac{\partial^2 T_2}{\partial r^2}+\frac{\partial^2 T_2}{\partial z^2}\right) \\ \rho_1 c_1\left(\frac{\partial T_3}{\partial t}+v_1 \nabla T_1\right)=k_1\left(\frac{1}{r}\frac{\partial T_3}{\partial r}+\frac{\partial^2 T_3}{\partial r^2}+\frac{\partial^2 T_3}{\partial z^2}\right) \\ \rho_4 c_4\frac{\partial T_4}{\partial t}=k_4\left(\frac{1}{r}\frac{\partial T_4}{\partial r}+\frac{\partial^2 T_4}{\partial r^2}+\frac{\partial^2 T_4}{\partial z^2}\right) \\ \rho_5 c_5\frac{\partial T_5}{\partial t}=k_5\left(\frac{1}{r}\frac{\partial T_5}{\partial r}+\frac{\partial^2 T_5}{\partial r^2}+\frac{\partial^2 T_5}{\partial z^2}\right) \\ \rho_e c_e\frac{\partial T_e}{\partial t}=k_e\left(\frac{1}{r}\frac{\partial T_e}{\partial r}+\frac{\partial^2 T_e}{\partial r^2}+\frac{\partial^2 T_6}{\partial z^2}\right) \end{cases} \tag{1}$$

Where T_1, T_2, T_3, T_4, T_5 and T_e are the temperature of inside pipe, pipe, annulus, casing, cement and formation, °C. k_1, k_2, k_4, k_5 and k_e are the thermal conductivity of drilling fluid, pipe, casing, cement and formation, W/(m·°C). ρ_1, ρ_2, ρ_4, ρ_5 and ρ_e represent the density of drilling fluid, pipe, casing, cement and formation kg/m^3. c_1, c_2, c_4, c_5 and c_e are the specific heat capacity of drilling fluid, pipe, casing, cement and formation, J/(kg·°C). r is radius, m. z *is* axial depth, m.

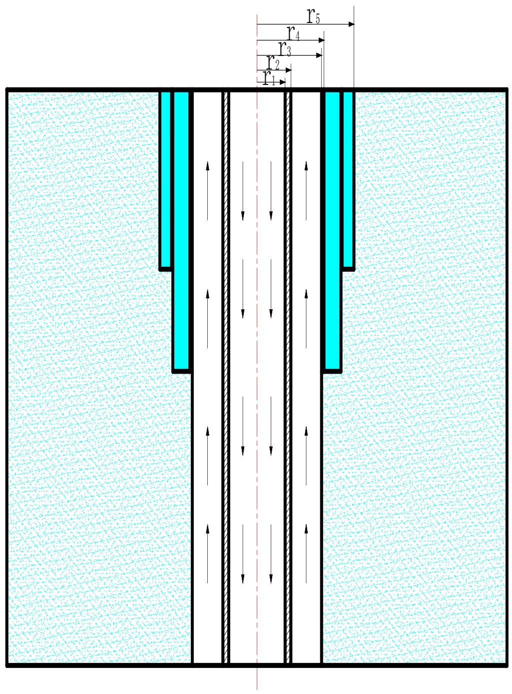


Fig 1. Circulation model parameter in the wellbore.

The initial and boundary conditions are shown in Eq. 2 and Eq. 3, respectively.

Initial conditions:

$$\begin{gathered} T_{z\to\infty} = T_{ei} \\ T_{r\to\infty} = T_{ei} \\ T_1(z=0) = T_{in} \\ -k_e\left(\frac{\partial T_e}{\partial r}\right)_{z=L} = -k_1\left(\frac{\partial T_b}{\partial r}\right)_{z=L} \end{gathered} \tag{2}$$

Boundary conditions

$$
\begin{aligned}
-k_1\left(\frac{\partial T_1}{\partial r}\right)_{r=0} &= 0\\
-k_2\left(\frac{\partial T_3}{\partial r}\right)_{r=r_1} &= -k_1\left(\frac{\partial T_1}{\partial r}\right)_{r=r_1}\\
-k_1\left(\frac{\partial T_3}{\partial r}\right)_{r=r_2} &= -k_2\left(\frac{\partial T_2}{\partial r}\right)_{r=r_2}\\
-k_4\left(\frac{\partial T_4}{\partial r}\right)_{r=r_3} &= -k_1\left(\frac{\partial T_3}{\partial r}\right)_{r=r_3}\\
-k_5\left(\frac{\partial T_5}{\partial r}\right)_{r=r_4} &= -k_1\left(\frac{\partial T_3}{\partial r}\right)_{r=r_3}\\
-k_5\left(\frac{\partial T_5}{\partial r}\right)_{r=r_4} &= -k_4\left(\frac{\partial T_4}{\partial r}\right)_{r=r_4}\\
-k_e\left(\frac{\partial T_e}{\partial r}\right)_{r=r_4} &= -k_5\left(\frac{\partial T_5}{\partial r}\right)_{r=r_5}
\end{aligned}
\qquad (3)
$$

Where r_1, r_2, r_3, r_4, r_5 are inner radius of pipes, outer radius of pipes, inner radius of cases, outer radius of cases and outer radius of cement, respectively, m; T_{in} is the inlet temperature, °C; T_b is bottom hole temperature, °C.

3. The main parameters of ZR$_1$

ZR1, which located at Guide Basin, Qinhai Province, China, is drilled to study hot dry rock and the depth is 3000m. The well structure is listed in Table 1.

Table 1 Basic data of drill string assembly and casing program

	Drilling Pipe	First casing	Second casing	Third casing
Inner diameter(mm)	80	228	162	-
Outer diameter(mm)	89	245	178	152
Depth(m)	3000	50	1500	3000

3.1 Initial formation tempearture

The initial formation temperature is shown in Fig. 2 which reflects the temperature distribution characteristic of fracture-convection type geothermal resources. The temperature rate has a sharp increase tendency when drilling into the geothermal conduit, the geothermal gradient is 102 °C /100m between 0 and 100 m. On the contrary the temperature rate flattens from 100 to 3000m, the geothermal gradient is 8℃/100m (100-200m) and 1.1 °C /100m (200-3000 m), respectively. It is indicated that the fractures in formation are developed (Li and Li, 2017). The bottom hole temperature reaches to 151 ℃.

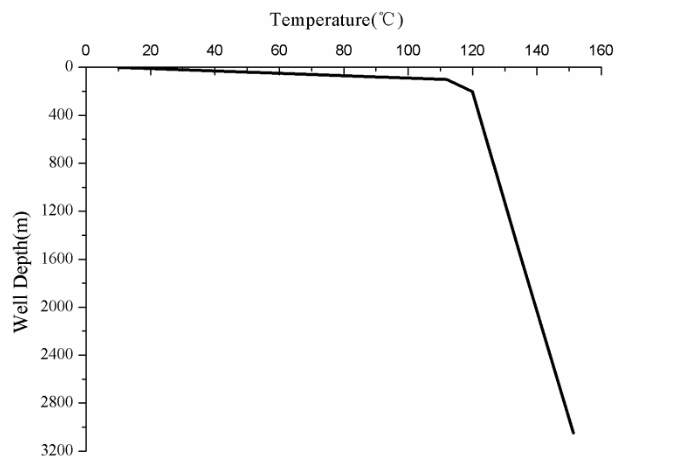


Fig.2 Initial formation temperature of ZR1(Zhao, 2016).

3.2 Thermophysical properties of materials and formation

The main rocks in the drilling area are mainly granite and granodiorite. The used casing is J55-type, and the pipe uses the same type. G hand gusher cement is used to cementing. The thermophysical properties of these are displayed in Table 2.

Table 2 Thermodynamics properties of the materials and formation.

	Density （kg/m^3）	Thermal Conductivity [J/(kg·°C)]	Thermal Capacity [W/(m·°C)]
Pipe and Casing	8000	400	43.75
Cement	1850	2000	0.70
Formation	2640	800	2.25

3.3 Thermophysical properties of drilling fluid

Sulfonated drilling fluid is the main drilling fluid used in ZR1, whose density, plastic viscosity and yield point are 1160 kg/m^3, 15 mPa and 3 Pa, respectively. The thermal conductivity and thermal capacity of drilling fluid are determined through the density (Santoyo-Gutierrez, 1997), the relations are shown as follow,

$$c_1 = 4186.8 - 3253.14SF$$
$$k_1 = 0.69 + 16.62SF$$
$$SF = 0.0798\left(\frac{\rho_1}{119.826} - 8.33\right) \quad 998.15 < \rho_1 \leq 1234.21 \qquad (4)$$
$$SF = 0.0318\left(\frac{\rho_1}{119.826} - 10.3\right) \quad \rho_1 > 1234.21$$

Where SF is the percentage of solids in drilling fluid.

The effective viscosity in pipe and annulus can be calculated by Eq.5 and Eq.6 respectively

$$\mu_1 = \mu_\mathrm{p} + \frac{\tau_0}{8(v_z/D_1)} \qquad (5)$$

$$\mu_2 = \mu_\mathrm{p} \frac{\tau_0}{8v_z/(D_3-D_2)} \qquad (6)$$

Where μ_1, μ_2 is the effective viscosity in pipe and annulus respectively, mPa·s; μ_p is plastic viscosity, mPa·s; D_1, D_2, D_3 is the diameter of inner pipe, outer pipe and inner annulus, respectively.

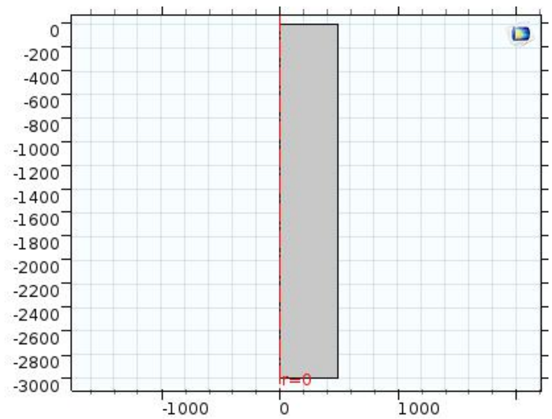
In summary, the thermophysical properties of drilling fluid are demonstrated in Table 3.

Table 3 Thermodynamics properties of drilling fluid

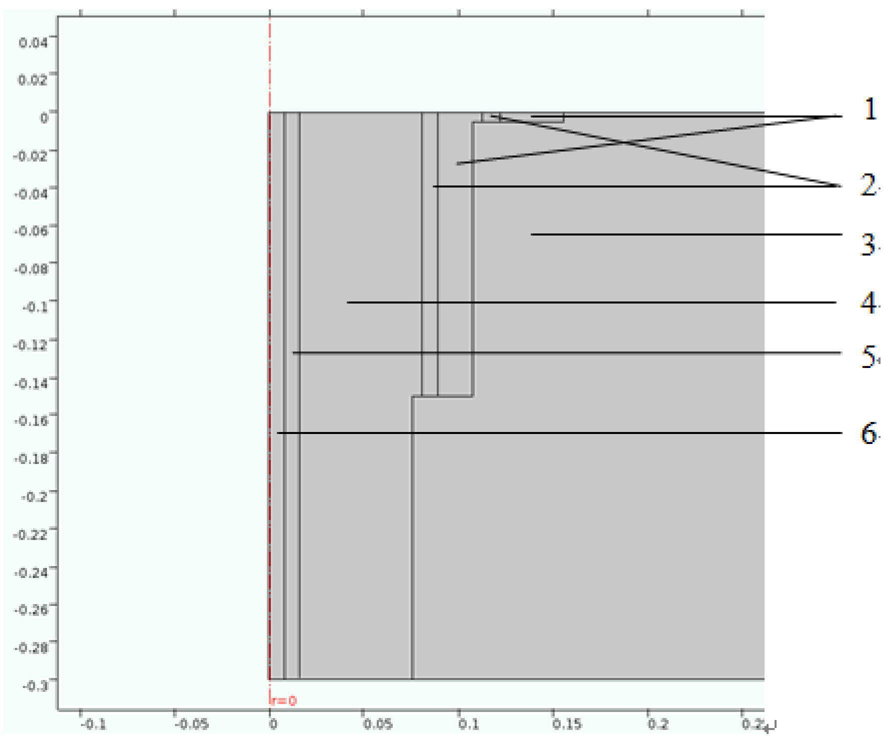
Parameter	Value
Density（kg/m^3）	1160
Plastic Viscosity (mPa)	15
Yield Point (Pa)	3
Thermal Conductivity [J/(kg·°C)]	3834
Thermal Capacity [W/(m·°C)]	2.48
Effective viscosity in pipe (mPa·s)	20
Effective viscosity in annulus (mPa·s)	25

4. Result and Discussion

COMSOL Multiphysics 5.2 is used to model the wellbore temperature of ZR_1. The model is set to a two-dimensional axisymmetric model. We set the depth of the model is 3000m and the influence radius is 500m (see Fig.3(a)). The aspect ratio of tubing, casing and cementing is excessively large, so we reduce the depth of 10000 times firstly, as shown in Fig.3(b), then the depth restores to original size after drawing the tubing, casing and cementing.



(a)



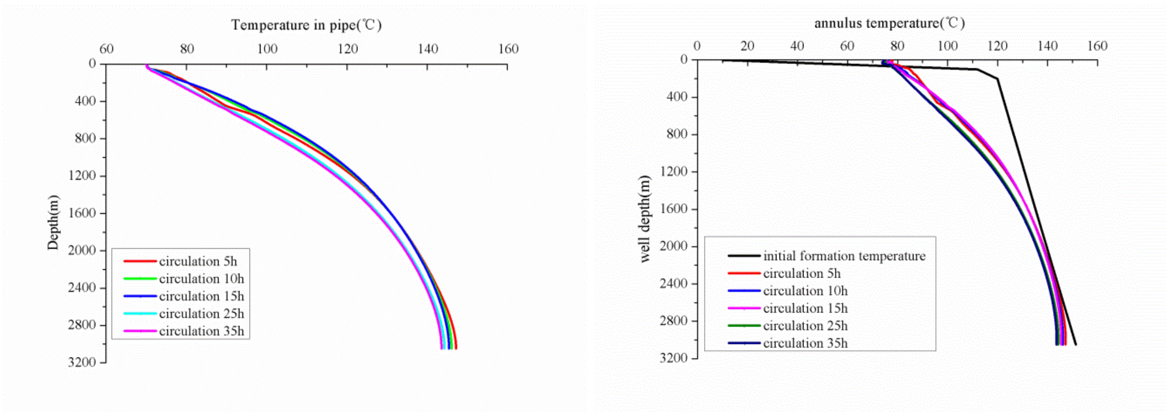
(b)

Fig.3 (a) the full-sized of the wellbore and formation model; (b) wellbore and formation model which the depth reduces 10000 times. (1)cementing; (2) casing; (3) formation; (4) annulus; (5) tubing; (6) fluid in the tubing

The discharge of drilling fluid is 18.2 L/s. As the formation temperature is high and lack of water, the temperature of circulation fluid increases to 70 °C rapidly, so we choose the 70 °C as the inlet temperature.

4.1 The wellbore temperature distribution with time

The relations of the temperature in bottom, pipe and annulus with time are shown as follow,



(a) (b)

Fig. 4 (a) The temperature of inner pipe in different cycle times; (b) The temperature of annulus in different cycle times

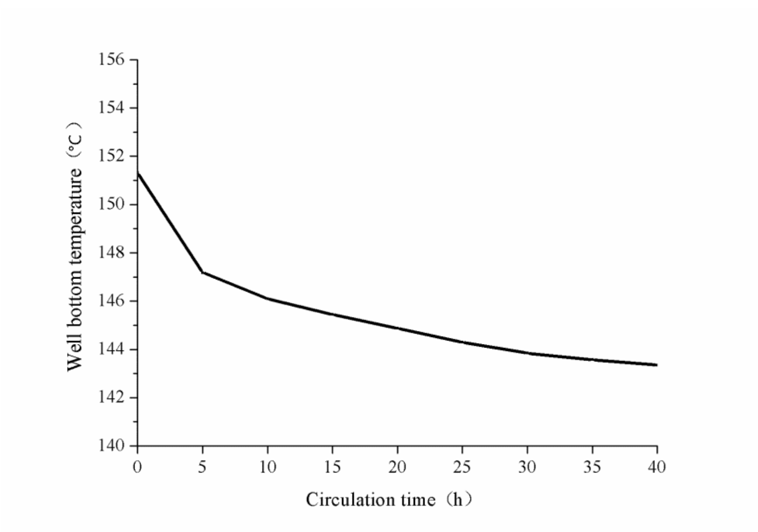


Fig. 5 Bottom temperature changes with time

The Fig. 4 and 5 demonstrate that (1) the wellbore temperature decreases with the time, (2) the temperature decreasing rate is fast in first 5 h and then gradually slow with the circulation, and (3) the location of the highest fluid temperature is at a point above the well bottom in the annulus instead of the well bottom.

The drilling fluid flows into the well and the heat transfer process occurs among the drilling fluid, pipe, casing and formation continuous, the heat in the formation transfers into the drilling fluid, then the heated drilling fluid flows up to the surface, and cools by the surrounding environment. The temperature difference between surrounding formation and wellbore is large in the early period of circulation, an amount of heat flow into the wellbore and the surrounding formation become cold gradually. As the circulation time grows, the impact on annular temperature wears off. The temperature difference between surrounding formation and wellbore lessens, the less heat transfers into the wellbore according to the Newton cooling theory. The heat transfer process tends to stable and the well bottom temperature remains nearly constant. The location of the highest fluid temperature is at a point above the well bottom because of the high formation temperature influence when the drilling fluid rises from the bottom.

The calculated outlet temperature is about 78 °C, which is close to the actual outlet temperature, 80℃. The error is mainly from the following aspects: (1) the thermal conductivity and thermal capacity of drilling fluid are not the measured; (2) the thermophysical properties of formation is the actual value as the formation is heterogeneous, the content of the rock in formation is random; (3) the initial formation temperature is not accurate as the temperature is calculated by the temperature logs, and (4) the heat convention information is ignored.

4.2 The wellbore temperature distribution with geothermal gradient

The previous wellbore temperature models are mainly built in study of oil well, and the geothermal gradient is considered as constant, while as the characteristics of geothermal, a single geothermal gradient is not applicable to the wellbore temperature study in geothermal well. Suppose the geothermal gradient is constant and the bottom temperature keeps the same, then the gradient becomes 4.63 °C /100m, use the gradient to calculate the wellbore temperature distribution (as shown in Fig.6)

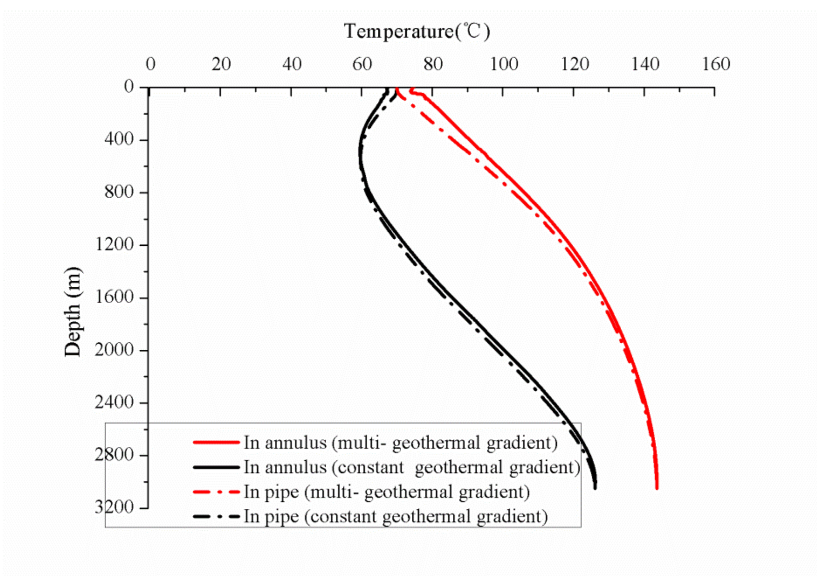


Fig. 6 The temperature comparison of wellbore after cycle 35h modeled with constant and multi-geothermal gradient

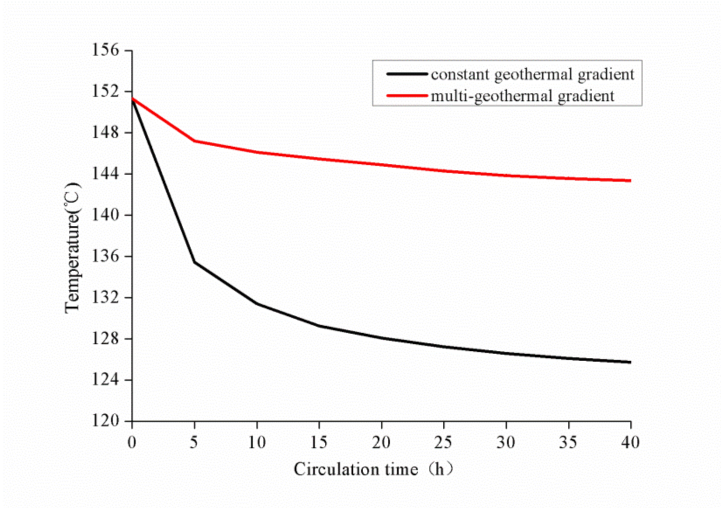


Fig. 7 Bottom temperature changes with time modeled with constant and multi geothermal gradient

As shown in Fig. 7, the calculated bottom temperature with constant geothermal gradient is much smaller than multi geothermal gradient and the wellbore temperature becomes lower and the calculated outlet temperature is 67 °C with the constant geothermal gradient. The actual formation temperature reaches to 112 °C at the depth of 100m, while the formation temperature is 14.63 °C in constant geothermal gradient system and changes the heat transfer process. In practice, the drilling fluid temperature in annulus is lower than the formation temperature at the depth of 100m, and the heat flows from the formation to the wellbore, while in the supposed system, the drilling fluid temperature in annulus is higher than the formation temperature at the same position, the heat transfer direction is contrary to the reality.

5. Conclusion

The wellbore temperature is an important parameter to safe drilling, so it is important to obtained the accurate wellbore temperature during circulation. In this paper, the wellbore heat transfer model was built based on the conservation of energy, and calculated the wellbore temperature distribution of ZR1. The result showed that the wellbore temperature decreases with the time and the temperature decreases fast in early period and then gradually slow with the circulation time.

Compared the calculated outlet temperature by the model with the actual temperature, the model accord with the actual basically, and the error of the model result from the inaccurate parameter. This model doesn’t take into account the heat convention caused by fluid filtration in formation, which is also a main source of error.

As the characteristic of geothermal well, the wellbore temperature model with constant geothermal gradient may generate severe error, deviated from the actual situation, so calculating the wellbore temperature should consider the multi-geothermal gradient.

The influence of heat convection in formation on wellbore temperature distribution will be researched in the future.

Acknowledgements: The authors thank two anonymous reviewers from Key Laboratory on Deep Geodrilling Technology of the Ministry of Land and Resources and National-level International S&T Cooperation Base of Geodrilling Equipment and Tools for their comments that greatly improved the mamuscript

REFERENCES

Verma, A., and Pruess, K. "Enhancement of Steam Phase Relative Permeability Due to Phase Transformation Effects in Porous Media." *Proceedings: 11th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA (1986). <Reference Style>

Wang, C.T., and Horne, R.N. "Boiling Flow in a Horizontal Fracture." *Geothermics*, 29, (1999), 759-772. <Reference Style>

Duan, C.Y, Zheng, X.H., Xia, B.R, et al. “Temperature Distribution Modeling in Geothermal Wellbore and Formation During the Well Test in Yangyi Geothermal Field, Tibet.” *PROCEEDINGS, Fourtieth Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, February 22-24, 2016

Espinosa-Paredes, G, Garcia A, Santoyo E, et al. “TEMLOPI/V. 2: a computer program for estimation of fully transient temperatures in geothermal wells during circulation and shut-in.” Computers & geosciences, 27(3), (2001), 327-344.

Hasan, A.R, Kabir. C.S, Ameen. M.M, et al. “A mechanistic model for circulating fluid temperature.” SPE , 1 (1996), 133-144.

Hasan A R, Kabir C.S. “Modeling two-phase fluid and heat flows in geothermal wells. ”Journal of Petroleum Science and Engineering, 71(1), (2010),77-86.

Hasan, A.R, Kabir, C.S, Wang, X. “A robust steady-state model for flowing-fluid temperature in complex wells.” SPE Production & Operations, 24(02), (2009), 269-276.

Holmes, C.S, Swift, S.C. “Calculation of circulating mud temperatures.” Journal of Petroleum Technology, 22(06), (1970), 670-674.

Kabir, C.S, Hasan, A.R, Kouba, G.E, et al. “Determining circulating fluid temperature in drilling, workover, and well control operations.” SPE Drilling & Completion, 11(02), (1996) ,74-79.

Keller, H.H, Couch, E.J, Berry, P.M. “Temperature distribution in circulating mud columns. ” Society of Petroleum Engineers Journal, 13(01), (1973), 23-30.

Li, D.Q., Kang, Y.L., Liu, D, W., et al. “Effect of temperature on safe drilling of ultra-deep well in non-hydration formations”. Oil Drilling & Prodution Technology, 30(6), (2008), 52-57.

Li, G.L., Li, G.X. “A discussion on the heat source mechanism and geothermal system of Gonghe- Guide basin and mountain geothermal field in Qinghai Province.” Geophysical and Geochemical Exploration, 41(1), (2017) : 29-34.

Liu, Y.S., Zhou, Y.H., Huang,K.L. “Influence of Borehole Temperature Variation on Shaft Wall Stability.” Oil Drilling & Prodution Technology, 18(4), (1996), 1-4.

Ramey, H.J. “Wellbore heat transmission. ”Journal of Petroleum Technology, 14(04), (1962), 427-435.

Raymond L.R. “Temperature distribution in a circulating drilling fluid.” Journal of Petroleum Technology, 21(03), 1969, 333-341.

Santoyo-Gutierrez E.R. “Transient numerical simulation of heat transfer processes during drilling of geothermal wells.” University of Salford, Salford, United Kingdom, 1997.

Wu B, Zhang X, Jeffrey R G. “A model for downhole fluid and rock temperature prediction during circulation.” Geothermics, 50, (2014), 202-212.

Wei, B.H., Lu, X.F., Wang, B.Y., “Study on Influence of Temperature Variation on Shaft Wall Stability in High Temperature Wells.” Drilling fluid & completion fluid, 21(6), (2004), 15-18

Wu B, Zhang X, Jeffrey R G. “A model for downhole fluid and rock temperature prediction during circulation.” Geothermics, 50, (2014), 202-212.

Yang M, Meng Y, Li G, et al. “Estimation of wellbore and formation temperatures during the drilling process under lost circulation conditions.” Mathematical Problems in Engineering, 2013, (2013), 1943-1997.

Yang, M., Meng, Y.F., Li, G. “Influence of radial temperature gradient and axial thermal conductivity of drilling fluid on temperature distribution of wellbore.” Acta Physica Sinica, 62(7), (2013a), 79101-079101.

Yang, M., Meng, Y.F., Li, G. “A New Method for Predicting the Temperature of the Original Stratum in the Whole Process of Drilling Based on the Principle of Proportional Integral Control.” Acta Physica Sinica, 62(7), (2013b), 179101-179101.

Zhao, F. S., Zhao, K.“Study on Drilling Technology of ZR1 Dry Hot Rock Well in Qinghai. ”Exploration Engineering Media. 43(2), (2016), 18-23.

Zheng, X.H.,Duan, C.Y, Ye, H.Y, et al. “Pressure Analysis and Balanced Drilling in Yangyi Geothermal Field of Tibet by Coupling with Temperature” *PROCEEDINGS, Fourtieth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, February 22-24, 2016

Zheng, X.H.,Duan, C.Y, Ye, H.Y, et al. “Equivalent Circulation Density Analysis of Geothermal Well by Coupling Temperature.” *Energies*, 268, (2017).