A Numerical Simulation Study on Wellbore Temperature Field of Water Injection in Highly Deviated Wells

Liu Jun[1, 2]*, Wang Wei[1], Zhang Jianzhong[3], and Xiao Guohua[3]

[1]School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu 610500, China
[2] Modern Design and Simulation Lab for Oil and Gas Equipment, Southwest Petroleum University, Chengdu 610500, China
[3]Drilling Technology Research Institute of Jidong Oil Field Company, Hebei, 063000, China

ABSTRAC

According to the temperature distribution of water injection well-bore in highly deviated wells under different conditions and unstable temperature field heat conduction principles, a true three-dimensional model was established to analyze the law of variation on temperature of highly deviated wells during the water injection process, and to analyze the factors that influence the water injection well-bore in highly deviated wells; this can improve the computational accuracy of the transformation of water injection string made by the temperature, and help us predicate the transformation of water injection string more accurately during the production process. The results show that the temperature distribution of highly deviated wells are greatly affected by water injection inlet temperature or injection of water inlet temperature, water injection rate, and water injection time. With the temperature field model of highly deviated wells made in this paper, the construction quality and oil production can be highly improved by reasonably controlling the temperature. All the findings which have been obtained form a theoretical basis and the experimental research for the development of mechanical analysis simulation software have been used to calculate temperature distribution and variation of water injection string in highly-deviated wells and have a great theoretical significance and practical value.

Keywords: Highly Deviated Well, Water Injection, Temperature Profile, Numerical Calculation, Experimental Research

INTRODUCTION

Currently, oil exploration and development in China are facing high pressure and high temperature environment, and simultaneously many development blocks are far from artificial islands and Jacket well location, so tilt angle and displacement are growing in wells. This type of oil is buried deeply, and well tilt angle and wellbore temperature change a lot. When string movement is restricted, a large temperature difference will result in stress and the deformation of large string changes, and then the safety of pipe string is affected [1]. Meanwhile, the formation fracture

***Corresponding author**
Liu Jun
Email: 99803392@qq.com
Tel: +13 438019245
Fax: +13 438019245

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pressure of reservoir can be easily affected by temperature [2], and the changing of wellbore temperature can easily lead to wellbore instability [3, 4]. Besides, the continuous injection of cold water into the formation makes temperature drop around bottom formation, and then produces the oil within the reservoir; thus the water viscosity changes, which will affect the oil displacement effect of water [5, 6]. Therefore, it is very significant that wellbore temperature field of water injection in highly deviated wells is accurately calculated. The true three-dimensional model is established to analyze the highly deviated well water injection process temperature variation and the influential factors of wellbore temperature field by unstable temperature field heat conduction principles herein so that the value of accurate temperature changes of the water injection in different working conditions could be calculated and the influential factors of wellbore temperature distribution could be analyzed. This research also provides valid data for the further analyses of temperature effect on the mechanical behavior caused by the temperature of the water injection string. Moreover, this research serves as a theoretical guidance for rational regulation of wellbore temperature.

THEORETICAL MODEL

Fundamental Assumptions

According to the actual situation of highly deviated wells injection wellbore temperature field, the following assumptions are put forward based on the numerical simulation models:

- Wellbore continuously and rigidly contact with pipe string, and the rigidity of pipe string is considered.
- The axis of pipe string is in accordance with the borehole axis.
- The hole trajectory of highly deviated wells is described by the Frenet formula [7].
- The computational element of the pipe string is a circular arc in the space on the inclined plane.
- Before water injection, the thermals status of the pipe string, fluid in the wellbore, and the ground are equal and in equilibrium situation. Simultaneously, the initial temperature distribution obeys a stable geothermal gradient change.
- After water injection, heat transfer is considered in the direction of wellbore radius and along the vertical depth; besides, during water injection, putting the original fluid in the wellbore extrusion of mass transfer causes heat conduction to be taken into account.
- When the wellbore temperature fields are discretized in the spatial domain, the properties of matters in each micro body domain such as heat transfer coefficient and specific heat are relatively stable.
- Water injection rate, water injection temperature, all the year round average temperature under the ground, and geothermal gradient are constant.
- Away from the wellbore axis enough in the distance of $r \geq R_{max}$, formation temperature is original ground temperature.
- Under the surface of the earth $Z=Z_m$, temperature T_m does not change over time; under the surface of the earth $Z>Z_m$, original formation temperature satisfies the linear relationship of $T_{dz}=T_m+\alpha z$, where α is the formation temperature gradient.
- By considering a variety of conditions in oil production operations, this important tip is found out that a process of injecting liquid from string and liquid flowing out from the wellbore annulus must be considered for the next process when the wellbore temperature field is calculated.

Establish Model

On the basis of the above assumptions, in order to the first law of thermodynamics, and the basic principles of heat transfer, the liquid in the tubing string, the string wall, liquid in the annulus, and stratigraphic unit were taken as the control volume in order to derive these control bodies energy balance equation and the mathematical model of temperature field. As shown in Figure 1, any infinitesimal bodies were taken as the control volume in the wellbore-stratigraphic system, and it was assumed that the radial distance is d*r*, and the borehole distance along the axial direction is d*z*.

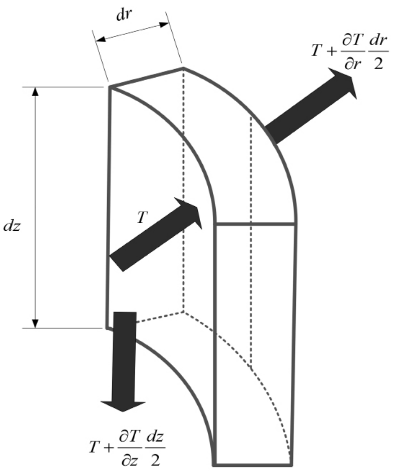

Figure 1: A schematic diagram of micro element body.

The micro unit center temperature is set as *T*, which, by Fourier heat conduction law, can be learned; at the place of *z*-d*z*/2 the temperature is *T*-(∂*T*/∂*z*)(d*z*/2); at the place of r+d*z*/2 the temperature is *T*+(∂*T*/∂*z*)(d*z*/2); at the place of *r*-d*z*/2 the temperature is *T*-(∂*T*/∂*r*)(d*z*/2); at the place of *r*+d*r*/2, the temperature is *T*+(∂*T*/∂*r*)(d*z*/2). For example, taking a unit of the pipe string is to establish a thermodynamic equilibrium equation. The thickness of a micro unit in the column is d*z*, and the radial distance is equal to the string inside radius r_{ti}. According to the assumptions, if the changes in fluid potential and fluid density were not considered, the heat of the micro element body carried over by the injected fluid from the top of wellbore per unit time may be written as follows:

$$Q_1 = c_f\,\rho_f\,\pi r_{ti}^2 v_f\left(T_f - \frac{\partial T_f}{\partial z}\frac{dz}{2}\right) \tag{1}$$

The heat of the micro element body carried over by the injected fluid from the bottom of wellbore per unit time may be written as given by:

$$Q_2 = c_f\,\rho_f\,\pi r_{ti}^2 v_f\left(T_f + \frac{\partial T_f}{\partial z}\frac{dz}{2}\right) \tag{2}$$

Respecting the convective heat transfer between fluid and pipe wall, and according to the Newton's law of convective heat transfer formula, the heat of the micro element body carried over from pipe wall per unit time can be given by

$$Q_3 = \alpha_{tf}\cdot 2\pi r_{ti}\,dz\left(T_t - \frac{\partial T_t}{\partial r}\frac{r_{to}-r_{ti}}{2} - T_f - \frac{\partial T_f}{\partial r}\frac{r_{ti}}{2}\right) \tag{3}$$

The heat of the micro element body carried over by friction per unit time reads:

$$Q_4 = \frac{1}{4}\pi\lambda_f\,\rho_f\,dz\,r_{ti}v_f^{\,3} \tag{4}$$

$$Q_5 = c_f\,\rho_f\,\pi r_{ti}^2 dz\,\frac{\partial T_f}{\partial t} \tag{5}$$

Heat energy variation per unit time in a micro element body can be defined as follows:

$$Q_1 - Q_2 + Q_3 + Q_4 = Q_5 \tag{6}$$

Using the heat balance principles, Equation 6 can be rewritten as follows:

$$\begin{aligned}&c_f\,\rho_f\,\pi r_{ti}^2 v\left(T_f - \frac{\partial T_f}{\partial z}\frac{dz}{2}\right) - \\ &c_f\,\rho_f\,\pi r_{ti}^2 v_f\left(T_f + \frac{\partial T_f}{\partial z}\frac{dz}{2}\right) + \alpha_{tf}\cdot 2\pi r_{ti}\,dz \\ &\cdot\left(T_t - \frac{\partial T_t}{\partial r}\frac{r_{to}-r_{ti}}{2} - T_f - \frac{\partial T_f}{\partial r}\frac{r_{ti}}{2}\right) \\ &+\frac{1}{4}\pi\lambda_f\,\rho_f\,dz\,r_{ti}v^{\,3} = c_f\,\rho_f\,\pi r_{ti}^2 dz\,\frac{\partial T_f}{\partial t}\end{aligned} \tag{7}$$

The thermal equilibrium given in Equation 7 can be transformed into the following form:

$$-c_f\,\rho_f\,r_{ti}\,v_f\,\frac{\partial T_f}{\partial z}+\frac{2}{r_{ti}}\alpha_{tf}\,(T_t-T_f\,)+\frac{1}{4r_{ti}}\lambda_f\,\rho_f v_f^{\;3}$$
$$=c_f\,\rho_f\,\frac{\partial T_f}{\partial t} \tag{8}$$

On the basis of the same principle, the heat balance equation of the other units can be established; the true three dimensional mathematical model of temperature field for wellbore-stratigraphic system can be defined as given below.

$$\begin{cases}
-c_f\,\rho_f\,r_{ti}v_f\,\dfrac{\partial T_f}{\partial z}+\dfrac{2}{r_{ti}}\alpha_{tf}\,(T_t-T_f\,)+\dfrac{1}{4r_{ti}}\lambda_f\,\rho_f v_f^{\;3}=c_f\,\rho_f\,\dfrac{\partial T_f}{\partial t}\\
k_t\,\dfrac{\partial^2 T_t}{\partial z^2}-2\alpha_{tf}\,\dfrac{r_{ti}}{r_{to}^2-r_{ti}^2}(T_t-T_f\,)+4k_t\,\dfrac{r_{to}}{\left(r_{to}^2-r_{ti}^2\right)\left(r_{to}-r_{ti}\right)}(T_a-T_t\,)=c_t\rho_t\,\dfrac{\partial T_t}{\partial t}\\
k_a\,\dfrac{\partial^2 T_a}{\partial z^2}-4k_t\,\dfrac{r_{to}}{\left(r_{ci}^2-r_{to}^2\right)\left(r_{to}-r_{ti}\right)}(T_a-T_t\,)+4k_a\,\dfrac{r_{ci}}{\left(r_{ci}^2-r_{to}^2\right)\left(r_{ci}-r_{to}\right)}(T_c-T_a\,)=c_a\rho_a\,\dfrac{\partial T_a}{\partial t}\\
k_c\,\dfrac{\partial^2 T_c}{\partial z^2}-4k_a\,\dfrac{r_{ci}}{\left(r_{co}^2-r_{ci}^2\right)\left(r_{ci}-r_{to}\right)}(T_c-T_a\,)+4k_c\,\dfrac{r_{co}}{\left(r_{co}^2-r_{ci}^2\right)\left(r_{co}-r_{ci}\right)}(T_e-T_c\,)=c_c\rho_c\,\dfrac{\partial T_c}{\partial t}\\
k_e\,\dfrac{\partial^2 T_e}{\partial z^2}-4k_c\,\dfrac{r_{co}}{\left(r_{ce}^2-r_{co}^2\right)\left(r_{co}-r_{ci}\right)}(T_e-T_c\,)+4k_e\,\dfrac{r_{ce}}{\left(r_{ce}^2-r_{co}^2\right)\left(r_{ce}-r_{co}\right)}(T_w-T_e\,)=c_e\rho_e\,\dfrac{\partial T_e}{\partial t}\\
\dfrac{\partial^2 T_w}{\partial z^2}+\dfrac{\partial^2 T_w}{\partial r^2}+\dfrac{1}{r}\dfrac{\partial T_w}{\partial r}=\dfrac{c_w\,\rho_w}{k_w}\dfrac{\partial T_w}{\partial t}
\end{cases} \tag{9}$$

where, C_f (J/(kg°C)) is the specific heat of the fluid in the tubing string; ∂t_f (W/(m²°C)) is the coefficient of convective heat transfer between fluid in the string and pipe wall; λ_f is the friction coefficient of the fluid in the string, which is related to fluid Reynolds number and flow pattern; ρ_f (kg/m³) represents fluid density in the string; v_f (m/s) stands for the speed of the fluid motion. k_t, k_a, k_c, k_e, and k_w are respectively the heat conductivity coefficient of injected fluid, cylinder wall, within the annulus fluid, formation rock, injection, and the original liquid mixing unit; Similarly, c_t, c_a, c_c, c_e, and c_w are respectively their specific heat capacity in J/(kg°C); ρ_t, ρ_a, ρ_c, ρ_e, and ρ_w are respectively their the density in kg/m³; r_{to}, r_{co}, r_{ci}, r_{ti}, and r_{ce} (m) are respectively the radius of the outer wall of pipe string, the radius of the outer wall of the casing, the string inner radius, the radius of the inner wall of the casing, and the cement ring diameter.

Boundary Conditions

When the wellbore temperature field model is established, boundary conditions are established as follows:

T_m is the temperature in somewhere under local annual average surface, and in general, it is a fixed value at the depth of 20 meters. Since the wellbore is axisymmetric, in the center of the hole diameter $(\partial T/\partial r)_{r=0}=0$. Besides, since infinity away from the center line of the hole diameter, $T_{r=Rmax}=T_{dz}$. The adiabatic boundary for bottom hole formation is $(\partial T/\partial z)_{z=l}=0$. The temperature of the fluid injected into from wellhead tubing or the annulus is constant; back to the exit of the boundary for the liquid temperature, $(\partial T/\partial z)_{z=0}=0$ [8].

Initial Conditions

According to the research condition in this paper, the initial conditions are established as follows:

When t=0, the temperature of wellbore and formation is the known formation temperature distribution. Since the recovery operation is carried out continuously during each process, the next working procedure of the initial temperature condition is one end of the previous process temperature conditions.

Working Condition

When water injection process temperature field was calculated, the heat conduction caused by mass transfer during fluid injection from wellhead and the original fluid in the wellbore, which is squeezed out, must be taken into account. U (m³/min) is the volume of injected fluid flow from wellhead. Since the injected fluid is liquid, the volume is always constant and equal to U. The velocity of fluid at the cross-section A_z of the fluid flow path along longitudinal Z can be written as:

$$u_z = U / A_Z \tag{10}$$

There are an L_m number of A_{zi} in the well depth of L (i=1, 2, ..., L_N), and then the total time t_L of injected fluid flow to the bottom of a well is worked out by:

$$t_L = \sum L_i A_{zi} / U \ (i = 1 \cdots L_N) \tag{11}$$

Several typical working conditions are considered as follows:

Condition one: when time is $t \le t_k$, there are a number of interfaces of $Z=Z_{ab}$ in the flow path. At the well depth of $Z<Z_{ab}$, the fluid is the injected fluid, meanwhile when $Z>Z_{ab}$, the original fluid is in the wellbore. Z_{ab} can be worked out by t, t_k, and μ_z. Therefore, a unit with two media mixing is appeared on space domain and satisfies the following heat balance equation:

$$\begin{aligned}&(c_o \rho_0 U T_{12} - c_1 \rho_1 U T_{34}) - \lambda_0 (\partial T - \partial n)_{So} - \lambda_1 (\partial T - \partial n)_{S1} \\ &= V_0 c_0 \rho_o (\partial T / \partial t)_{vo} + V_1 c_1 \rho_1 (\partial T / \partial t)_{v1}\end{aligned} \tag{12}$$

Units below the well depth of $Z<Z_{ab}$ and $Z>Z_{ab}$ are the same fluid, which satisfies the following heat balance equation:

$$c_i \rho_i U (T_{12} - T_{34}) - \lambda_I (\partial T / \partial n)_S = V_i c_i \rho_i (\partial T / \partial t)_V \tag{13}$$

Condition two: when time is $t>t_k$, there are no mixed units, and then the heat can be calculated by Equation 1.

Condition three: when the fluid in the oil tube and oil casing is static and stagnant, there are several dielectric interfaces in the flowing path and more than two kinds of medium mixing unit in spatial domain as shown in Figure 2. The actual distribution and heat transfer near the interface of two kinds of different medium within the cell are extremely complex, but all can be solved by the heat balance Equation 2 and Equation 3.

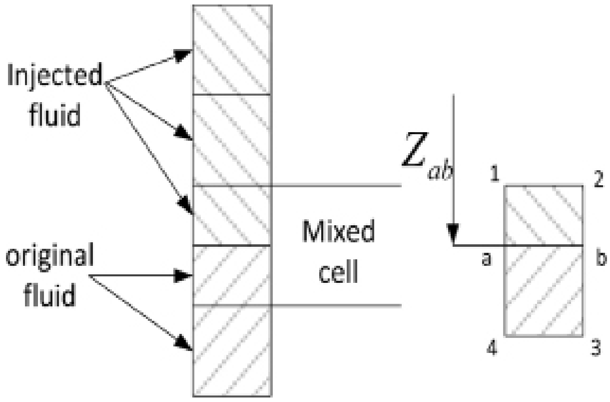

Figure 2: Fluid mixing units.

Solution Method for Model

The spatial domain is discrete by high precision of isoparametric elements adopted in this paper, and an optional implicit finite difference time domain of variable step is used in loop iteration, which obviously improves the accuracy and effectiveness of the calculation of the whole temperature field [9,10]. Next, the established temperature field model is solved by FORTRAN language programming, which is used to analyze the effect of different factors on the wellbore temperature distribution.

Factors Influencing the Temperature of Highly Deviated Well Water Injection Wellbore

As an example, the parameters of a high angle well showed in Tables 1 and 2 are used to analyze the law of wellbore temperature field distribution with the various influential factors [11]. The controllable factors in the process of water injection included a water injection rate, water inlet temperature, water injection time, etc. In addition, wellbore temperature will also be affected by environmental factors and the structure of the borehole, etc.

Table 1: Parameters of highly deviated well.

Parameter Name	Value	Parameter Name	Value
Drill pipe inner diameter (m)	0.031	Specific heat of string (KJ/kg°C)	0.11
Drill pipe outer diameter (m)	0.0365	Thermal conductivity of string (W/m^2°C)	0.64
Inner casing diameter (m)	0.06068	Cement sheath diameter (m)	0.3
Outer casing diameter (m)	0.06985	Specific heat of cement sheath (KJ /kg°C)	0.21
Specific heat of formation (KJ/kg°C)	0.25	Specific heat of water (KJ/kg°C)	1.0
Well depth (m)	2955	Water injection rate (m/s)	0.2
Thermal conductivity of formation (W/m^2°C)	0.02	Thermal conductivity of cement sheath (W/m^2°C)	0.016

Table 2: Parameters of wellbore trajectory.

Well depth (m)	Deviation angle (°)	Azimuth (°)	Well depth (m)	Deviation Angle (°)	Azimuth (°)
0	0	82.08	1673.88	4.85	301.27
231.47	0.69	40.48	1962.03	0.85	328.45
521.99	1.26	246.32	2260.76	2.41	23.14
810.03	0.83	277.98	2548.93	2.32	160.57
1097.78	11.28	301.58	2819.09	0.72	143.98
1385.81	15.24	298.55	2955.7	0.13	269.33

Impact of Injection Water Inlet Temperature on the Temperature Distribution of Highly Deviated Wellbores

The inlet temperature of water is a very important factor in oil field development. Under the conditions of a depth of 2955.7 m, a water injection rate of 0.15 m^3/min, and a water injection time of 120 min, adjusting different water inlet temperature and the chart about wellbore temperature change law of the highly deviated well are displayed in Figure 3. When the inlet temperature of water varies from 15 to 40°C, the bottom hole temperature increases by about 10°C. That is, improving the wellhead injection water temperature is equivalent to increasing more energy entering the wellbore by the pump, which increases the temperature of bottom hole. The amplitude of the increase in bottom hole temperature is associated with an increased range of inlet temperature of the water injection; however, the temperature distribution of wellbore is not obviously affected by the water inlet temperature.

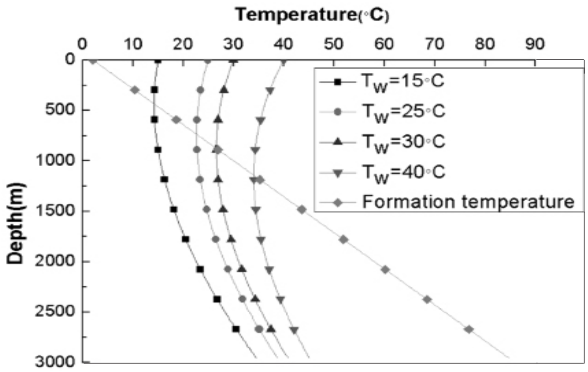

Figure 3: Wellbore temperature profiles and water temperature curve.

Impact of Water Injection Rate on the Temperature Distribution of Highly Deviated Wellbores

Water injection rate plays an important role in oil field development [12]; under the conditions of a water injection time of 120 min and a water injection initial temperature of 15°C, water injection rate is respectively 0.05, 0.08, 0.10, and 0.12 m^3/min; the wellbore temperature profile curves are presented in Figure 4. Figure 4 shows that when the water injection rate is low, injection water and rock stratum around the wellbore have sufficient time exchanging heat; therefore, the wellbore temperature is more close to the ambient temperature than the higher water injection rate. With increasing the water injection rate, the convective heat transfers between the injected water and environment time is accordingly reduced. Eventually, the temperature of bottom wellbore is decreased.

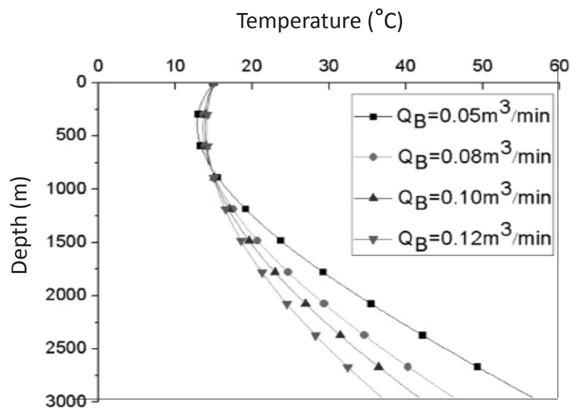

Figure 4: Wellbore temperature profiles and water injection rate curves.

Impact of Water Injection Time on the Temperature Distribution of Highly Deviated Wellbores

Wellbore temperature is higher in a shorter injection time as shown in Figure 5. With increasing injection time, the temperature of formation around the wellbore is reduced. Also, when heat exchange between wellbore and formation tends to be stable, wellbore temperature is relatively low.

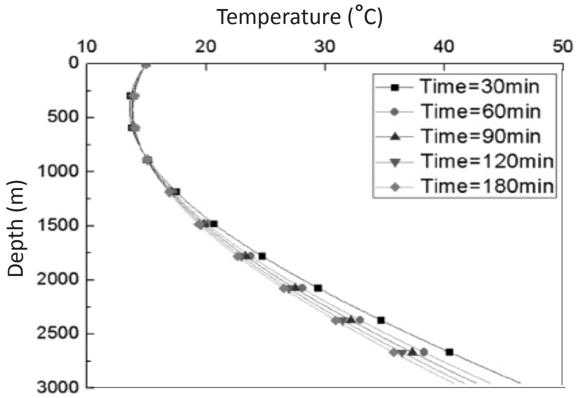

Figure 5: Wellbore temperature profiles and water injection time curves.

Impact of Geothermal Gradient on the Temperature Distribution of Highly Deviated Wellbores

Under the conditions of a water injection time of 120 min, a water injection initial temperature of 15°C, and a water injection rate of 0.1 m^3/min, wellbore temperature profiles and geothermal gradient curves are presented in Figure 6. The picture shows that with increasing geothermal gradient, wellbore temperature increased significantly. As the well becomes deeper, the temperature of the bottom hole becomes higher and higher. Hence, the precise prediction of the geothermal gradient willhave a great influence in order to predict wellbore temperature profile [13].

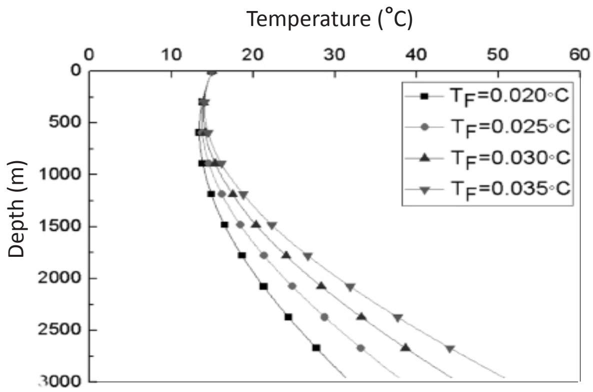

Figure 6: Wellbore temperature profiles and geothermal gradient curves.

The Experiment to Measure the Temperature Field Distribution

The stress measurement system of the downhole stringis composed of two parts: the downhole string stress test device and the computer data acquisition software. As shown in Figure 7, the downhole string stress test device is connected to the working string in the pipe string and to the measures.

The tester structure diagram is shown in Figure 8. The measuring device is built in a single-chip controlled manner by setting the sampling and external pressure, temperature, axial load, and torque data, and the data collected by the single-chip are stored in the memory. When the operation is finished, the data in the test device is transferred through dedicated communication lines to computer data software. As shown in Figure 9, the temperatures of different depths and injection water times were measured by the tester and used in Jidong oil field. At the well depth of 30 m, the temperature of the wellbore is about 16°C. It is low and does not change over the injection time. At a depth of 2854 m, close to bottom hole, the temperature is about 82°C, and reduces obviously over the injection water time. Near the wellhead, the temperature of water is close to the temperature of the stratum, and the heat transfer is not obvious. When the well depth is larger, the temperature difference of water and stratum heavily causes heat transfer, and then the corresponding wellbore temperature is decreased; finally thermal equilibrium is established.

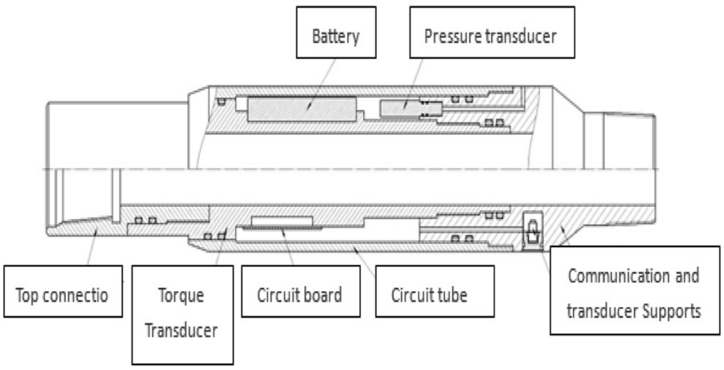

Figure 7: Tester structure diagram.

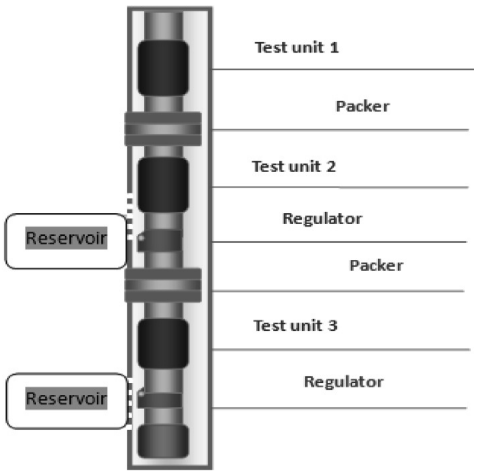

Figure 8: A schematic diagram of test process.

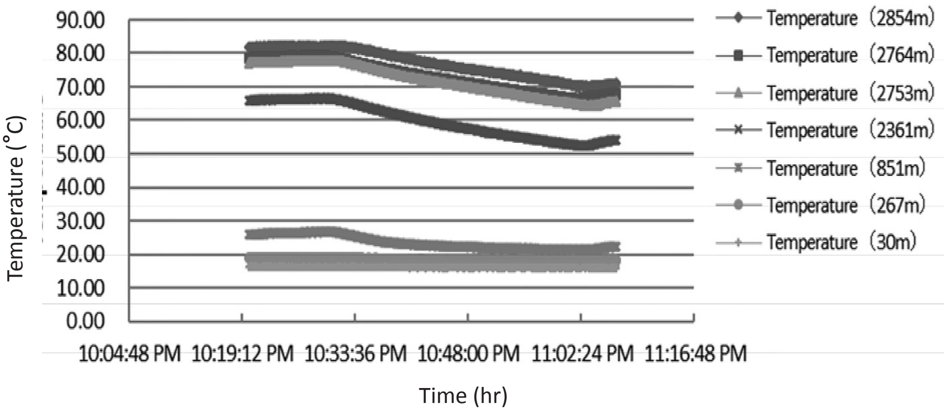

Figure 9: The temperature of different depths and injection water times.

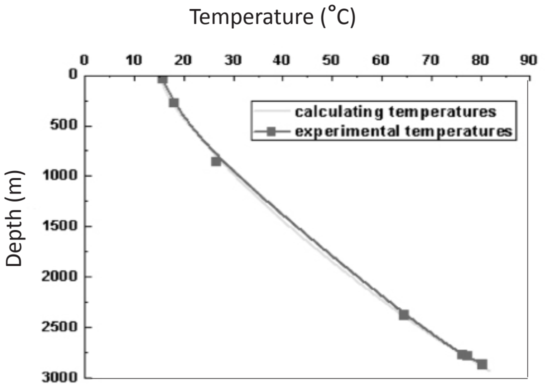

Figure 10: Comparison of the experimental and theoretical results.

CONCLUSIONS

The true three-dimensional model which has been proposed in the current paper can accurately calculate the distribution of temperature in different water injection conditions; besides, this model can provide technical support to prevent wellbore temperature [14] from becoming too high and thus producing a larger temperature stress and avoiding borehole wall collapse [15] in the process of water injection. Figure 10 shows that the results of the experiments and in good agreement with the theoretical calculations. Additionally, water inlet temperature does not obviously affect the wellbore temperature distribution except for water injection rate, water injection time, and geothermal gradient. It is necessary that the geothermal gradient be accurately measured and then water injection rate and water injection time, in descending order, be reasonably controlled. The results are consistent with those reported in the literature [14]. Finally, the results have a great theoretical significance and practical value.

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