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Temperature prediction of oil well during circulation of compressible aerated fluids with leakage

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ABSTRACT

Aerated fluids drilling has been widely used when drilling conventional oil wells, unconventional gas well and geothermal wells for many reasons. The main reason to use aerated fluids is that the technique can minimize circulation losses and prevent the formation from damaging. This paper studied the temperature distribution of oil well with high temperature, when the wells were drilled with aerated fluids and circulation losses occurred at the same time. A coupled wellbore flow model was developed considering the interaction between pressure distribution and temperature distribution. Then the temperature distribution was solved using MATLAB Software accounting for the transient heat transfer because of aerated fluids leakage into the reservoir. The simulation result shows that compared with the temperature prediction model assuming no gas compressibility, the temperature distribution model considering gas compressibility can fit field data better and the new model can predict the temperature distribution of aerated fluids with circulation losses well. When gases injected into the well increased, the temperature in the annulus at the wellhead increased at the same time, but the temperature at the bottom showed the opposite phenomenon. The increment of circulation losses will reduce the temperature of aerated fluids, but the effect is not much.

1. INTRODUCTION

Aerated fluids drilling is widely used for drilling conventional oil wells, unconventional gas wells and geothermal wells, because the use of aerated fluids can minimize circulation losses of drilling fluids, increase penetration rate, use lesser water and protect formation [1-2]. Aerated fluids, which have been proven to make positive effect on drilling, consist of air, aerated liquid, mist, or foam fluid systems to make the density of the drilling fluid little. The prediction of temperature field and pressure distribution in the oil wells and surrounding formation during drilling and completion are very important. These parameters play an important role in the evaluation of thermal conductivities of the certain oil wells and the design and impletion of drilling fluids.

At present, there are several methods to determine the temperatures and pressures in oil or gas wells during drilling. One common used empirical model was developed by API [3] and Farris [4]. Barnett and You Z [5-6] developed a new model which considered the property change of drilling fluid with the well depth to calculate the pressure and temperature distribution in gas wells. A closed mathematic model was developed by Li J and Gou B [7-8] to predict the temperature distribution in a gas well of unconventional tight gas reservoir during drilling with gas, and the paper shows that the flow rate of gas is one main factor influencing the bottom hole temperature. In the past, there are some models which were developed to solve the problem of the heat transfer between wellbore and surrounding reservoir during drilling fluid circulation. The effects of circulation losses during drilling have not be well studied. The prediction of temperatures distribution in a geothermal well during circulation with lost circulation is done by A. Garcia and E. Santoyo [9]. Gilberto Espinosa-Paredes [10] studied the thermal behavior of drilling fluids and the surrounding rock when water and gas and conventional muds are used as drilling fluids in geothermal wells. However, these models cannot be used directly to predict downhole temperatures and pressures during drilling with aerated fluids with circulation losses in oil wells [11-14]. Because the property of gases in the aerated fluids is not constant and can change with pressure and temperature.

This paper presents a coupled wellbore flowing model considering the interaction between pressure distribution and temperature distribution. The coupled wellbore model considered the effect of the compressibility of aerated fluids and the circulation losses on the temperature distribution and pressure distribution. The calculation was based on MATLAB software. Finally, the temperature and pressure distribution were got. The results are compared with data from well YL29 in Sichuan Basin.

2. PHYSICAL MODEL AND ASSUMPTIONS

The physical model of a typical oil wells during drilling is shown in Fig.1 and the model and simulation of the distribution of temperature and pressure is based on the physical model. The temperature and pressure distribution of aerated fluids in the wellbore depends on several processes which can be seen in Fig.1. Five regions were classified during the model and simulation of temperature and pressure distribution. Region 1: the aerated drilling fluid passes through the drilling pipe in z direction with the velocity of v_z and the temperature at the inlets is specified T_{in}, the temperature distribution and pressure distribution are determined by mechanism of heat convection in the pipe and heat exchange with the drill pipe. Region 2: the temperature of the drill pipe is determined by the mechanism of heat convection between the drill pipe metal wall and the mixed fluid in the drill pipe, at the same time the temperature depends on the heat convection between fluid flow in the annulus and drill pipe, as well as the heat conduction in the pipe metal. Region 3: In this region, the temperature distribution and pressure distribution depended on the heat convection of aerated drilling fluids with cuttings in the annulus and heat exchange between the annulus and the drill pipe wall, as well as heat exchange between the reservoir formation and the annulus. Region 4: it is the boundary of the well. Region 5 is the reservoir formation.

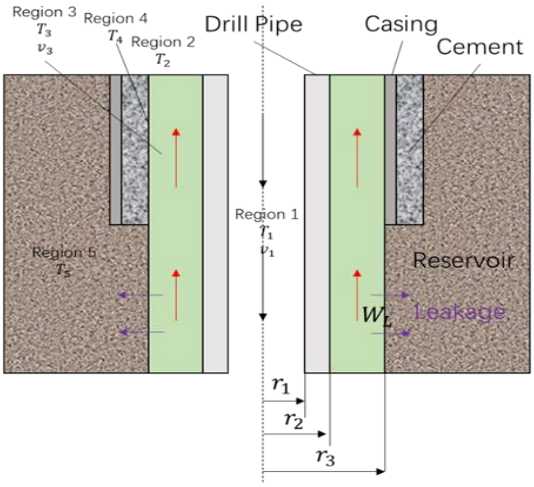

Figure 1. Physical model of a typical oil well wells during drilling

The model and simulation are based on the following assumptions:

(1) The properties of drill pipe and reservoir are homogeneous and isotropic;

(2) The flow in the pipe is considered as two-phase flow (gas and mud) and the flow in annulus is considered as two-phase flow (gas and mud with cuttings);

(3) The properties of the reservoir formation and pipe metal are constant;

(4) Heat transfer in region 1 and region 3 is by axial convection and by axial and radial conduction;

(5) Heat transfer in region 2 and region 4, 5 is by axial conduction and radial conduction;

(6) Only gas and water can flow into the reservoir.

3. COUPLED MODEL BETWEEN TEMPERATURE AND PRESSURE

The energy balances equations governing five regions are shown as following:

$$\rho_i Cp_i\left(\frac{\partial T_i}{\partial t}+v_{z,i}\frac{\partial T_i}{\partial z}\right)=\frac{k_i}{r}\frac{\partial T_i}{\partial r}+k_i\frac{\partial^2 T_i}{\partial r^2}+k_i\frac{\partial^2 T_i}{\partial z^2} \qquad (1)$$

where subscript i = 1,2,3,5 represent region 1, region 2, region 3 and region 5. r is in the radial direction, z is in the axial direction. ρ is the density of mixed fluid flowing in the drilling pipe and annulus, C_p is the specific heat of the material in each region, T is the temperature, $v_{z,i}$ is the flow velocity of drilling fluids in each region, k is the thermal conductivity of the material in each region.

The mass conservation equations for compressible gas and incompressible mud flow in drilling pipe and annulus are shown below:

$$\frac{1}{r}\frac{\partial(\rho_l r v_r)}{\partial r}+\frac{\partial(\rho_l v_{zl})}{\partial z}=0 \qquad (2)$$

For the gas phase:

$$\rho_g=\frac{Mp_g}{Z_g R T_i} \qquad (3)$$

where M is the molar mass of gas, R is the molar gas constant, 8.314 J/(mol.K).

$$\frac{M}{rR}\frac{\partial\left(\frac{p_g r v_{rg}}{Z_g T_i}\right)}{\partial r}+\frac{M\partial\left(\frac{p_g r v_{zg}}{Z_g T_i}\right)}{R\partial z}=0 \qquad (4)$$

For the mud phase, mud density is constant:

$$\frac{1}{r}\frac{\partial(r v_{rm})}{\partial r}+\frac{\partial(v_{zm})}{\partial z}=0 \qquad (5)$$

The initial condition:

$$T(r,z,t=0)=f(z) \qquad (6)$$

The boundary conditions:

$$q=-k_i\left(\frac{\partial T_i}{\partial r}\right)_{\text{int}}=h_i\left(T_s-T_f\right) \qquad (7)$$

$$\left(\frac{\partial T_1}{\partial r}\right)_{r=0}=0 \qquad (8)$$

$$v_{0,1}=\frac{W}{\rho A_d} \qquad (9)$$

where T_s is the temperature of drilling pipe or reservoir formation, T_f is the temperature of aerated drilling fluid, h_i is the heat transfer coefficient in each region, W is the mass flow rate of aerated drilling fluid in the drill pipe, A_d is the cross-sectional area of drill pipe.

The mathematical model for the circulation losses into reservoir formations:

$$\left(\rho C_p\right)_{ef}\left(\frac{\partial T_f}{\partial t}+v_r\frac{\partial T_f}{\partial r}\right)=\frac{k_{ef}}{r}\frac{\partial T_f}{\partial r}+k_{ef}\frac{\partial^2 T_f}{\partial r^2}+k_{ef}\frac{\partial^2 T_f}{\partial z^2} \qquad (10)$$

where k_{ef} represents the effective thermal conductivity which is related with the porosity of the reservoir and the thermal conductivities of the aerated drilling fluid.

The circulation losses (W_l) of aerated drilling fluid can be calculated with the Peaceman's wellbore equation as follows:

$$W_g = \frac{\rho_g k_f k_{rg}}{\mu_g} \frac{2\pi h}{\ln\left(r_e / r_w \right) + s} \left(p_{ah} - p_e \right) \tag{11}$$

$$W_w = \frac{\rho_w k_f k_{rw}}{\mu_w} \frac{2\pi h}{\ln\left(r_e / r_w \right) + s} \left(p_{ah} - p_e \right) \tag{12}$$

$$W_l = W_g + W_w \tag{13}$$

where W_l is circulation losses of aerated drilling fluid, W_g is circulation losses of gas into the reservoir formation, W_w is the circulation losses of water into the reservoir formation, k_f refers to the permeability of the reservoir formation, k_{rg} is the relative permeability of the formation to gases, k_{rw} is the relative permeability of the formation to water.

4. COMPUTATION AND RESULTS

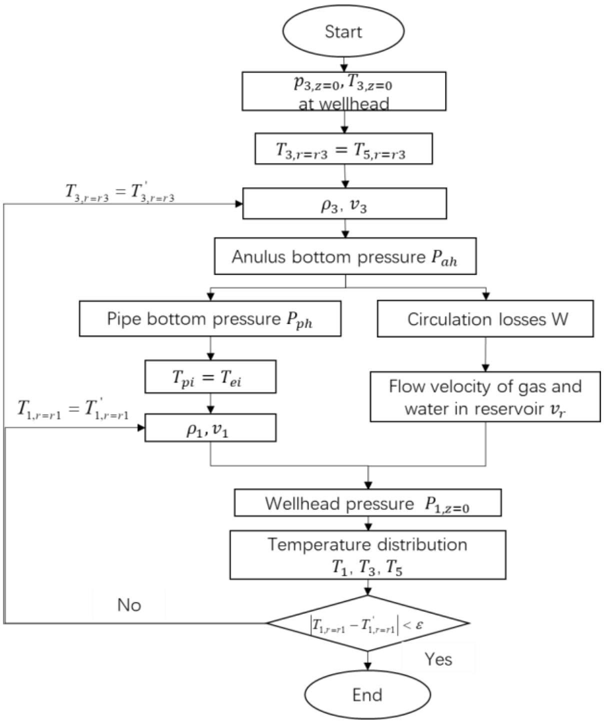

Figure 2. Diagram to calculate the temperature and pressure in and around the well

Table 1. The input parameters in the simulation

Physical parameter	Values
Well length	3340 m
Ground temperature	20 ℃
Temperature gradient	3.83 ℃/100m
Casing (Inside diameter)	222.4 mm
Drill pipe (outside diameter)	127 mm
Drill pipe (inside diameter)	108 mm
Well diameter	216 mm
Thermal conductivity (Casing)	46.6 W/(m · ℃)
Thermal conductivity (Cement)	0.35 W/(m · ℃)
Thermal conductivity (Formation)	2.0 W/(m · ℃)

The code and calculation of the temperature and pressure distribution in the wellbore is based on the following flowing diagram. Part of the data used in the model are listed in table 1, which is collected from YL29 well in Sichuan Basin. Finally, the modeling results are compared with the field data of YL29 well.

The temperature distributions in the drill pipe, the annulus and the formation considering the gas compressibility and assuming no gas compressibility are shown in Figure 3. Compared with the temperature distribution of fluids in drill pipe assuming no gas compressibility, the temperature distribution considering gas compressibility is a little higher at lower depth, because when the gases are compressed, the heat exchange rate becomes fast. Compared with the temperature distribution of fluids in annulus assuming no gas compressibility, the temperature distribution considering gas compressibility is a little lower at lower depth, because when the gases are compressed, the heat exchange rate becomes fast and the aeriated fluid are cooled down faster. And the field data are also used to test the reliability of the coupled model. The result shows that the field data of YL29 well fits the coupled model well. The temperature of aerated fluids in the annulus is higher than the temperature of the fluid in the pipe at the same depth. The temperature of fluids in the pipe is lower than the temperature in the formation at the same depth and the curve of temperature of fluids in annulus will coincide with the curve of formation. The figure 4 shows the effect of gas rate injected in the drilling fluid on the temperature distribution in the annulus. When the gas injected into the well increased, the temperature in the annulus at the wellhead increased, but the temperature at the bottom decreased. The reasons for the phenomenon are that heat capacity of aerated fluids decreases with the increment of gas injected and the velocity of the mixed fluids will increase. When the mixed fluids with the same mass flow in the annulus, the heat exchange rate becomes slow. So, the temperature profiles of annulus are much different with different injected gas rate.

The figure. 5 shows the effect of circulation losses on the temperature distribution of aerated fluids in the pipe. The result showed that with the increment of circulation losses the temperature of aerated fluids at the same depth decreased. But the circulation losses had litter effect on the temperature distribution of aerated fluids in the annulus. The calculated temperature distributions in radial direction in the surrounding rock at different depths are shown in Figures. 6. We can see that the temperature in the radial direction at the wellhead increased firstly and then decreased to the formation temperature. The temperature in the radial direction at the depth of 1000 meter shows increment a little firstly and then decreased a little to the formation temperature. The temperature in the radial direction at the depth of 2000 meter increased a little to the formation temperature.

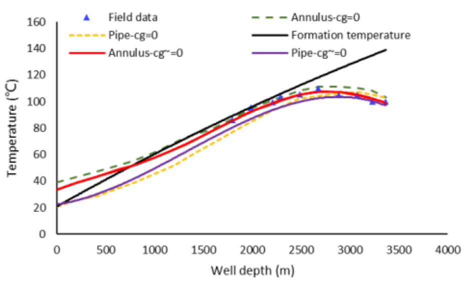

Figure 3. The compare of temperature prediction and temperature measured in the YL29 well

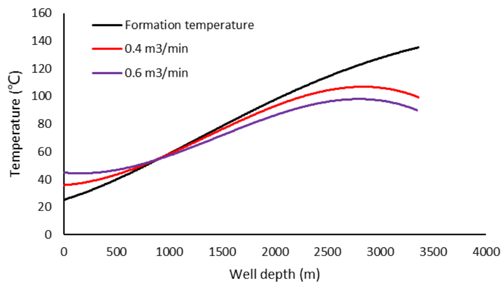

Figure 4. The effect of gas rate on the temperature distribution in the annulus

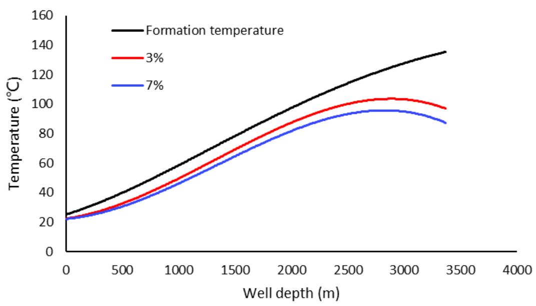

Figure 5. The effect of circulation losses on the temperature distribution in the pipe

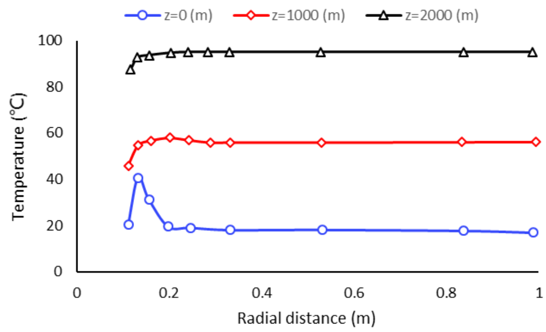

Figure 6. Temperature distribution in the radial direction at different well depth

5. CONCLUSION

To describe the temperature distribution in and around oil well during aerated drilling with circulation losses, a coupled wellbore flowing model was developed considering the interaction between pressure distribution and temperature distribution and the compressibility of the drilling fluids. Field data can fit the coupled model well and the new model can predict the temperature distribution of aerated fluids with circulation losses well. Compared with the temperature distribution of fluids in drill pipe assuming no gas compressibility, the temperature distribution considering gas compressibility is a little higher at lower depth, because when the gases are compressed, the heat exchange rate becomes fast. Compared with the temperature distribution of fluids in annulus assuming no gas compressibility, the temperature distribution considering gas compressibility is a little lower at lower depth, because when the gases are compressed, the heat exchange rate becomes fast and the aeriated fluid are cooled down faster. When the gas rated injected into the well increased, the temperature in the annulus at the wellhead increased, but the temperature at the bottom decreased. The reasons for the phenomenon are that heat capacity of aerated fluids decreases with the increment of gas injected and the velocity of the mixed fluids will increase. At the same time, the heat exchange rate becomes slow. The circulation losses had litter effect on the temperature distribution of aerated fluids in the annulus. The temperature in the radial direction at the wellhead increased firstly and then decreased to the formation temperature. The temperature in the radial direction at the depth of 1000 meter shows increment a little firstly and then decreased a little to the formation temperature. The temperature in the radial direction at the depth of 2000 meter increased a little to the formation temperature.

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NOMENCLATURE

A	the cross-sectional area, m^2
C	specific heat of the material, $J/(kg \cdot K)$
h	heat transfer coefficient, $W/(m^2 \cdot K)$
k	thermal conductivity, $W/(m^2 \cdot K)$
M	the molar mass of gas, g. mol^{-1}
p	pressure, Pa
r	the radial length, m
R	the molar gas constant, 8.314 J/(mol.K)
t	time, s
T	temperature, K
v	flow velocity of drilling fluids, m. s^{-1}
W	mass flow rate, kg.s^{-1}
z	depth, m
Z	Gas compression factor, dimensionless

Greek symbols

ρ	fluid density, kg.m^{-3}

Subscripts

d	drill pipe
e	external boundary
f	mud fluid
g	gas fluid
i	1,2,3,4,5 region
m	mud
r	the radial direction
m	mud
s	solid material
w	water
z	in the vertical direction
ef	effective value
int	initial condition
rg	relative permeability of gas
rw	relative permeability of water