A TEMPERATURE-PRESSURE COUPLING MODEL FOR PREDICTING GAS TEMPERATURE PROFILE IN GAS DRILLING

by

Jinjiang LIU**, *Wenlin WU, Peng QIAN, and Shuo WANG

Drilling and Production Technology Research Institute, PetroChina,
Liaohe Oilfield Company, Bijing, China

Original scientific paper
https://doi.org/10.2298/TSCI200314193L

In the gas drilling design, accurate prediction of wellbore temperature profile is very crucial. Different from liquid drilling fluid, physical and thermophysical parameters of gases are sensitive to the change of pressure and temperature, at the same time, the change of these parameters will react against the wellbore temperature and pressure. Based on the energy conservation principle, a temperature-pressure coupling calculation model was established to predict the gas temperature profile during gas drilling process. The model is solved by cycle coupling iteration method. The calculation shows that annular temperature rises sharply near the wellhead, drops sharply at bottom hole and is a little higher than the formation temperature in other places. Without considering the influence of friction heat, calculated temperature is lower than the actual temperature. Temperature trends are the same under different pump rates and larger pump rate leads to larger temperature range at the wellhead and at bottom hole. Compared with the pump rate, bit nozzle size has more influence on the temperature drop range. Temperature reduction increases from 31.3-57.2 ℃ while bit nozzle size decreases from 539-339 mm^2.

Key words: *gas drilling, temperature, coupling calculation, numerical analysis*

Introduction

With the increasing difficulty of oil and gas exploitation, more and more oil and gas resources in the shale and carbonate reservoirs have been discovered and explored. However, fractures are always well developed in these kinds of reservoirs, which result in the occurrence of a loss circulation. Compared with the traditional drilling fluid, annulus pressure is lower in gas drilling, so the loss circulation can be avoided partly. Therefore, gas drilling is more and more widely used in drilling wells.

In the drilling design, accurate prediction of wellbore temperature is important for achieving better fluid property and wellbore pressure. Compared with the traditional drilling fluid, such as water-base drilling fluid or oil-base drilling fluid, gas is a kind of easily compressible medium. Physical and thermophysical properties of gases are sensitive to the change of pressure and temperature, at the same time, the change of these parameters will react against the wellbore temperature and pressure. Therefore, it is more necessary to predict the wellbore temperature profile accurately during the gas drilling and master its change rule.

* Corresponding author, e-mail: liujinj@126.com

A number of researchers have studied the temperature distribution of drilling fluid in the wellbore during the drilling operation. Ramey [1] presented an approximate solution the wellbore heat-transmission problem involved in the injection of hot and cold fluids. In the model, heat transfer in the wellbore was considered as steady-state. Edwarson [2] modified Ramey's model by considering the influence of formation temperature. Raymond [3] presented a transient heat transfer model without considering the influence of heat source. A numerical method was used for the solution. Holmes and Swift [4] presented a model to calculate wellbore temperature under the condition of pseudo-steady flow state. Based on the research of Raymond, Keller *et al.* [5] presented a model considering 2-D transient heat exchange in the formation. The influence of the heat source on the temperature was also analyzed. The model showed that the heat source has a great influence on the annular temperature. Marshall and Bentsen [6] developed a computer model to solve the finite-difference equations describing transient heat transfer in the wellbore and analyzed the influence of some parameters on the wellbore temperature profile. Kabir *et al.* [7] presented a mathematical model for calculating the wellbore temperature in different operations. In this model, the bottom-hole temperature was assumed constant. Espinosa-Paredes *et al.* [8] developed a program which could estimate the initial transient temperature distribution of the drilling fluid. The 2-D transient heat transfer during drilling and shut-in conditions were considered in the numerical model. Wu *et al.* [9] developed a coupling numerical model for predicting the wellbore temperature profile. Hasan *et al.* [10, 11] presented a unified method which could present the heat behavior under different conditions. Analysis for single-phase and multi-phase flow was provided. Zhang *et al.* [12] used an analytical model to predict the bottom-hole temperature and thermal stress under steady- and unsteady-state were analyzed. Yang *et al.* [13, 14] presented a coupling numerical model for wellbore-formation transient heat transfer. Influence of actual downhole string assembly and casing program was analyzed. Yang *et al.* [15] presented a synthetic transient heat transfer model to calculate the wellbore temperature in the dynamic deepwater multi-gradient drilling. The model was solved using the combination of finite volume method and dynamic laying method. Li *et al.* [16] analyzed the temperature reduction at the well bottom and its effect on the rock failure. Li *et al.* [17] presented an analytical model with closed form equation predict the wellbore temperature profile in gas-drilling and identified the possible sources of error of the model. The influences of Joule-Thomson cooling and drilling cuttings were considered in the model. Li *et al.* [18] presented a numerical model to predict the wellbore temperature profile for gas-hydrate well drilling. It was found that Joule-Thomson cooling effect below the drill bit nozzle diminished rapidly in a short interval above the bottom hole. Li *et al.* [19] developed a theoretical CO_2 wellbore flow model and solved the model by coupling pressure and temperature.

In summary, a lot of models have been developed in the past decades for predicting the wellbore temperature profile. However, most of these models were developed for the liquid drilling fluid and physical and thermophysical properties of drilling fluid were assumed constant, while physical and thermophysical properties of gases were sensitive to the change of pressure and temperature. In order to improve the accuracy of gas drilling design and ensure drilling safety, it is necessary to calculate the wellbore temperature in the gas drilling and understand the influence of the drilling parameters, such as pump rate, nozzle size, on the wellbore temperature profile. The objective of the study is to develop a temperature-pressure coupling calculation model to predict the wellbore temperature profile in the gas drilling. The effect of heat source and Joule-Thomson cooling effect, interaction between temperature-pressure and gas parameters are all considered in the model. The model is solved by cycle coupling iteration method. In addition, a sensitivity study is carried out to investigate the influence of some related parameters, such as bit nozzle size and pump rate*, etc.*, on the wellbore temperature profile.

Physical model

The physical model of gas-flow in the well is illustrated in fig. 1. As the fig. 1 shows, during the drilling process, the whole circulation consists of three stages [20]:

– Gas enters the drill pipe at the wellhead and flows down the drill pipe. In this stage, gas enters the drill pipe with certain temperature. When gas-flows down the drill pipe, gas temperature is mainly influenced by the convection heat transfer between the inner wall of the drill pipe and the gas in the drill pipe.
– Gas-flows through the bit nozzle and enters the annulus at the bottom hole. In this stage, under the influence of Joule-Thomson cooling effect, the gas temperature drops sharply when it flows through the bit nozzle. The gas temperature in the downstream of the drill bit is much lower than the gas temperature in the upstream of the drill bit.
– Gas-flows up the annulus to the surface. In this stage, gas-flows upwards to the surface in the annulus, the temperature is mainly influenced by the heat generated by friction and the convection heat transfer between the inner wall of the casing pipe and the gas in the annulus, and between the outer wall of the drill pipe and the gas in the annulus.

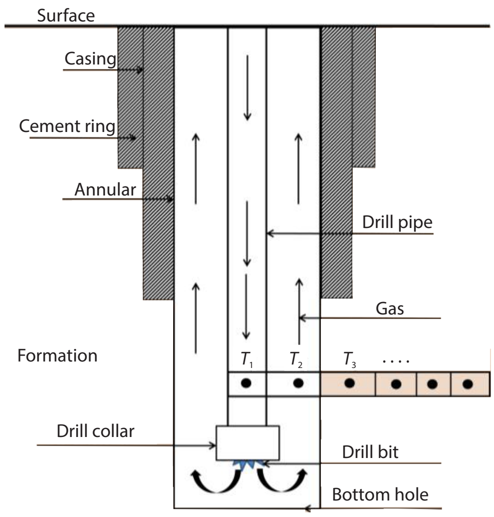

Figure 1. The physical model of gas-flow during circulation period

Mathematical model

Fundamental assumption

– Gas injection temperature is equal to the surface temperature.
– Rock density, casing pipe density and drill pipe density are constant. Thermophysical parameters of rock, casing pipe and drill pipe, such as specific heat and thermal conductivity, are constant.
– Formation temperature gradient is known and the calculation of initial formation temperature is based on the linear change.
– The heat generated by the drill bit breaking rock is ignored. The influence of rock debris on the gas temperature is ignored.
– Time step is very short. In each iteration, physical and thermophysical parameters of gases have little change, which can be ignored.

Thermal model development

In relation the overall circulation in the gas drilling, five heat transfer regions are needed to be identified:

– the drill pipe,
– the pipe wall,
– the annulus,
– the casing pipe or the wellbore wall, and
– the formation.

Transient heat exchange model in the drill pipe

When gas enters the drill pipe with certain temperature and flows down, gas temperature is determined by [21, 22]:
- heat carried by the downward flowing gas,
- convection heat transfer between drill pipe and gas in the drill pipe,
- heat generated by the friction between gas and drill pipe, and
- internal energy of gas changes with time.

The equation that describes the gas temperature in the drill pipe can be expressed:

$$Q_\mathrm{p} - \rho_\mathrm{g} q c_g \frac{\partial T_1}{\partial z} - 2\pi r_1 h_1 \left(T_1 - T_2\right) = \rho_\mathrm{g} c_\mathrm{g} \frac{\partial\left(\pi r_1^2 T_1\right)}{\partial t} \tag{1}$$

Transient heat exchange model of the drill pipe

The drill pipe separates the gas in the drill pipe from the gas in the annulus. The drill pipe temperature is determined by:
- heat generated by the vertical heat conduction of the drill pipe,
- convection heat transfer between gas in the pipe and the inner wall of the drill pipe, gas in the annulus and the outer wall of the drill pipe, and
- the internal energy of the drill string changes with time.

The equation that describes the drill pipe temperature can be expressed:

$$k_\mathrm{p} \frac{\partial^2 T_2}{\partial z^2} + \frac{2 r_1 h_1}{\left(r_2^2 - r_1^2\right)}\left(T_1 - T_2\right) + \frac{2 r_2 h_2}{\left(r_2^2 - r_1^2\right)}\left(T_3 - T_2\right) = \rho_\mathrm{g} c_\mathrm{p} \frac{\partial T_2}{\partial t} \tag{2}$$

Transient heat exchange model in the annulus

When gas-flows through the bit nozzle and flows up in the annulus, the gas temperature is determined by:
- heat carried by the upward flowing gas,
- the convection heat transfer between gas in the annulus and the outer wall of the drill pipe, gas in the annulus and the inner wall of the casing pipe or wellbore,
- heat generated by the friction between gas and drill pipe, gas and wellbore wall, and
- internal energy of gas changes with time.

The equation that describes the gas temperature in the annulus can be expressed:

$$Q_\mathrm{a} + \rho_\mathrm{ga} q c_\mathrm{g} \frac{\partial T_3}{\partial z} + 2\pi r_2 h_2 \left(T_2 - T_3\right) + 2\pi r_3 h_3 \left(T_4 - T_3\right) = \rho_\mathrm{ga} c_\mathrm{g} \pi \left(r_3^2 - r_2^2\right) \frac{\partial T_3}{\partial t} r \tag{3}$$

Transient heat exchange model in the formation

Based on the energy balance, heat transfer model at the interface of the wellbore wall (casing wall) can be expressed:

$$k_\mathrm{w} \frac{\partial T_4}{\partial r} = h_3 \left(T_4 - T_3\right) \tag{4}$$

Under the influence of well structure, k_w differs at different depth. In the casing section, k_w is equal to the thermal conductivity of casing pipe. In the open-hole section, k_w is equal to the thermal conductivity of rock.

Formation temperature is mainly influenced by the radial and vertical heat conduction. Considering calculation simplicity, rock anisotropy is ignored. Radial thermal conductivity is equal to the vertical thermal conductivity. The temperature distribution in the formation is expressed:

$$\frac{\partial^2 T_\mathrm{i}}{\partial z^2}+\frac{\partial^2 T_\mathrm{i}}{\partial r_\mathrm{i}^2}+\frac{1}{r_\mathrm{i}}\frac{\partial T_\mathrm{i}}{\partial r_\mathrm{i}}=\frac{\rho_\mathrm{i} c_\mathrm{i}}{k_\mathrm{f}}\frac{\partial T_\mathrm{i}}{\partial t} \tag{5}$$

Dittus-Boelter equation is applied to the calculation of convection heat transfer coefficient. The specific calculation method can be referred to the reference [21]. Specific heat capacity of gas is regarded as constant.

Transient heat exchange model at the bottom hole

In the previous models of the wellbore temperature profile, it was always assumed that the temperature of drill fluid, drill pipe and borehole wall were same at the bottom hole. However, when calculating the wellbore temperature profile for the gas drilling, this assumption is not accurate. When gas-flows through the bit nozzle during gas drilling, under the influence of Joule-Thomason cooling effect, gas temperature drops dramatically. The gas temperature in the downstream of the bit can be expressed:

$$T_\mathrm{dn}=T_\mathrm{up}\left(\frac{P_\mathrm{dn}}{P_\mathrm{up}}\right)^{k'-1/k'} \tag{6}$$

Heat source item

In the gas drilling, drill pump system and rotation system provide hydraulic energy and mechanic energy, respectively. Some of the energy is used to break rock and carry cutting, the rest is consumed in the form of heat, which will affect the wellbore temperature distribution. The heat sources consist of three parts: heat generated by the friction, heat generated by the rotation of drill pipe, and heat generated by rock breaking of bit. In this article, only the heat generated by the friction is considered. The heat can be expressed:

$$Q=q\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right) \tag{7}$$

Pressure model development

According to the law of conservation of mass and the theorem of momentum, the formula calculating the pressure drop in the drill pipe can be expressed:

$$\frac{\mathrm{d}P}{\mathrm{d}z}=-\rho v_\mathrm{i}\frac{\mathrm{d}v_\mathrm{i}}{\mathrm{d}z}+\rho \mathrm{g}-f\frac{\rho v_\mathrm{i}^2}{2D_\mathrm{i}} \tag{8}$$

For the same reason, the formula calculating the pressure drop in the annulus can be expressed:

$$\frac{\mathrm{d}P}{\mathrm{d}z}=-\rho v_\mathrm{o}\frac{\mathrm{d}v_\mathrm{o}}{\mathrm{d}z}-\rho \mathrm{g}-f\frac{\rho v_\mathrm{o}^2}{2D_\mathrm{o}} \tag{9}$$

It is usually considered that, in the gas drilling, the gas-flow pattern in the annulus is turbulent flow. In this kind of flow pattern, roughness has more influence on the friction coefficient than the Reynolds number. Friction coefficient equation is defined [23-26]:

$$f=\left[\frac{1}{1.74-2\log\left(\frac{2e}{d_H}\right)}\right]^2 \tag{10}$$

According to the aerodynamics, pressure in the downstream and upstream of bit has the following critical relationship [27, 28]:

$$\frac{P_{\mathrm{dn}}}{P_{\mathrm{up}}}=\left(\frac{2}{k'+1}\right)^{k'/k'-1} \tag{11}$$

The calculation of pressure drop between P_{up} and P_{dn} at the bit is based on the flow state. The specific calculation equation can be referred to the reference [23].

Initial and boundary conditions

– The initial temperature of gas in the pipe and annulus, wellbore or casing, drill pipe are same at any depth and equal to the original formation temperature at the same depth. The relationship between initial formation temperature and depth can be expressed [29, 30]:

$$T=T_{\mathrm{s}}+g_f H \tag{12}$$

– It is assumed that formation temperature far away from the wellbore is undisturbed, which means it is equal to the original formation temperature:

$$\left.\frac{\partial T_h}{\partial r}\right|_{r\to\infty}=0 \tag{13}$$

$$T_{\mathrm{i}}\left(r\to\infty,z,t\right)=T_{\mathrm{s}}+g_f H \tag{14}$$

– No heat exchange occurs between the surface formation and atmosphere:

$$T(r,z=0,t)=T_{\mathrm{s}} \tag{15}$$

Numerical solution

The numerical model can be transformed into a fully implicit finite form and Gauss-Seidel iteration method is used to solve the algebraic equations. The quality of grid is important to the accuracy of the calculation. In general, in the situation that the vertical length of the grids are less than 3% of the total well depth, the accuracy of the calculation can be ensured. The radial element size is increased as the exponential relationship. A cycle coupling iteration method is used to solve the model [31-34]. The flow chart of the calculation is shown in fig. 2.

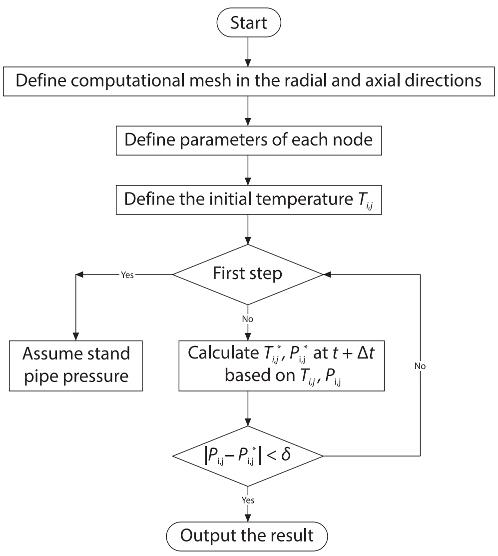

Figure 2. The flow chart of the coupling calculation

Case study

The following is an example to analyze the wellbore temperature profile during gas drilling. The data of this example are taken from reference [23]. The depth of the well in the example is 3048 m, bit diameter is 200 mm, outer diameter of the drill collar is 158.8 mm, and the length of the drill collar is 152.4 m. Pump rate is 0.8 m^3/s. Bit nozzle size is 539.0 mm^2. The surface temperature is 25 °C and the geothermal gradient is 0.03 °C. The other data used in the model are provided in tabs. 1 and 2.

Table 1. String assemble and casing program

Parameter	Outer diameter [mm]	Inner diameter [mm]	Depth [m]
Drill string	139.7	121.3	3048.0
Casing	219.0	201.2	2133.0

Table 2. Thermophysical parameters of each media

Parameter	Density [kgm^{-3}]	Specific heat [$Jkg^{-1}°C^{-1}$]	Thermal conductivity [$Wm^{-1}°C^{-1}$]
Gas	1.25	1040	0.024
Pipe	8000	400	43.75
Cement	2140	1000	0.7
Rock	2650	800	2.25

Figure 3 shows the wellbore temperature profile after four hours of circulation. Different from the wellbore temperature profile with liquid drilling fluid, temperature in the pipe increases almost parallel with the formation temperature. At the bottom hole, when gas-flows through the bit nozzle, the gas temperature drops dramatically under the influence of the Joule-Thomson cooling effect.

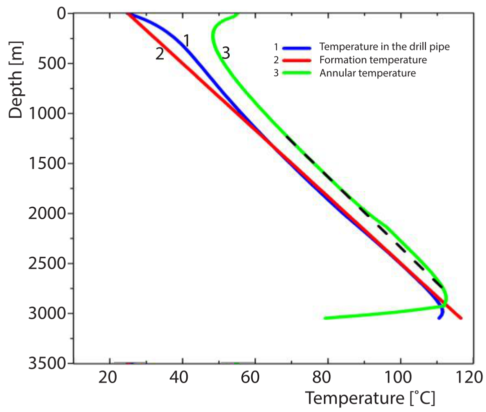

Figure 3. Model-predicted wellbore temperature profile

According to the eq. (10), the faster the gas-flow velocity is or the rougher the wellbore is, the larger the friction is and more heat is generated. At the drill collar, as the wellbore is rough and the annular cross-section becomes narrow which makes gas-flows faster, more heat is generated and annular temperature increases rapidly.

When gas-flows into the casing section, as casing roughness is smaller than the wellbore roughness, the friction heat decreases compared with that in the annular open-hole section. From the black dashed line in fig. 3, it can be seen that annular temperature trends in the casing section and open-hole section are approximately same, which are both parallel with the formation temperature, but the temperature difference between annulus and formation in the open-hole section is larger than that in the casing section. When gas-flows up to the wellhead, under the influence of pressure reduction, gas expands and gas-flow velocity rises rapidly, leading to the friction heat increases. So the annular temperature trend reverses near the wellhead, which increases fast. On the other hand, under the influence of annular temperature, temperature in the pipe increases faster near the wellhead than in the deep.

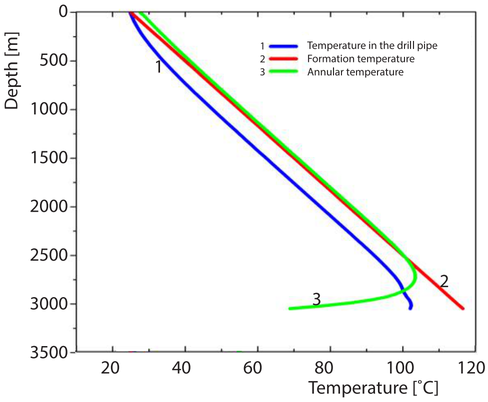

Figure 4. Model-predicted wellbore temperature profile without considering the heat source

The wellbore temperature profile without considering the influence of heat source is shown in fig. 4. Comparing with fig. 3, it indicates that heat source has great influence on the gas temperature distribution in the drill pipe and annulus. Without considering the heat source, although the temperature trends are still parallel with the formation temperature in most parts of well section, temperature, no matter in the pipe or annulus, are 5-10 °C lower than that in the situation of considering the heat source. At the bottom hole, there is little difference in the temperature reduction, but bottom-hole temperature differs largely. Bottom-hole temperature is 79 °C considering the heat source and it is 69 °C without considering the heat source. When gas-flows up from the bottom hole, it takes longer time for the annular temperature to recover without considering the influence of heat source. As shown in fig. 4, without considering the influence of heat source, annular temperature at the bottom hole increases in curve rather than in line.

Figure 5 shows the wellbore temperature profile with flow rate of 1 m^3/s. By comparison with fig. 3, it can be found that, under the condition of different flow rates, the trends of the wellbore temperature profile are similar, but temperature ranges near the wellhead and at the bottom hole are a little different. Figure 6 shows the annular temperature profile with different flow rates. Except the wellhead and the bottom hole, annular temperature increases with the increase of gas-flow rate. This is because that larger gas-flow rate means faster flow velocity and more friction heat. The temperature differences under different flow rates are small. At the bottom hole, temperature reduction range increase with the increase of the gas-flow rate. Temperature reduction increases from 31.3-36.3 °C while gas-flow rate increases from 0.8-1.2 m^3/s, so does the outlet temperature. Outlet temperature increases from 55.1-81.1 °C while gas-flow rate increases from 0.8-1.2 m^3/s.

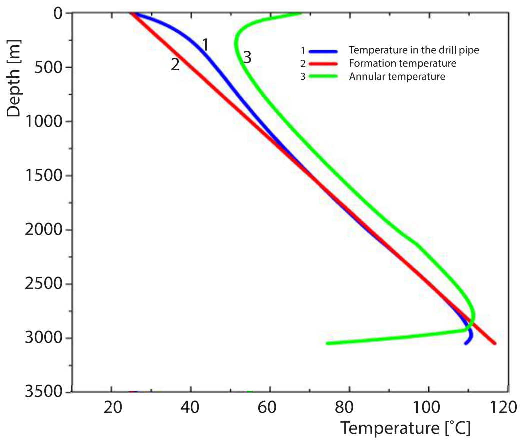

Figure 5. Model-predicted wellbore temperature profile with pump rate of 1 m^3/s

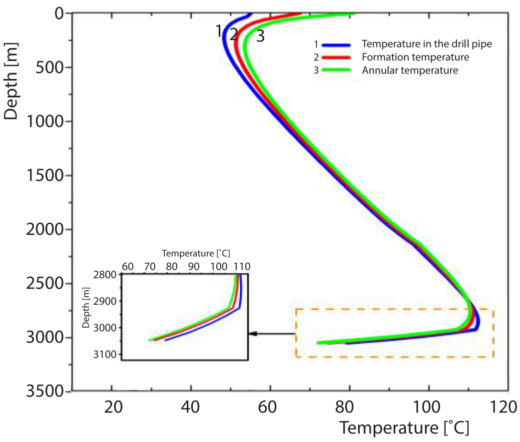

Figure 6. Model-predicted annular temperature profile with different pump rates

Figure 7 shows the wellbore temperature profile with bit nozzle size of 339 mm^2. A comparison between figs. 3 and 6 shows that bit nozzle size has great influence on the temperature reduction range at the bit. Temperature reduction increases from 31.3-57.2 °C while bit nozzle size decreases from 539-339 mm^2. It can be indicated that the smaller the bit nozzle size is, the larger the temperature reduction range is. After gas-flows up a distance from the well bottom, the wellbore temperature tends to be same. This means that the bit nozzle size only affects the temperature near the bottom hole. On the other hand, compare with the influence of the flow rate, the nozzle area is the primary influencing factor of temperature reduction range.

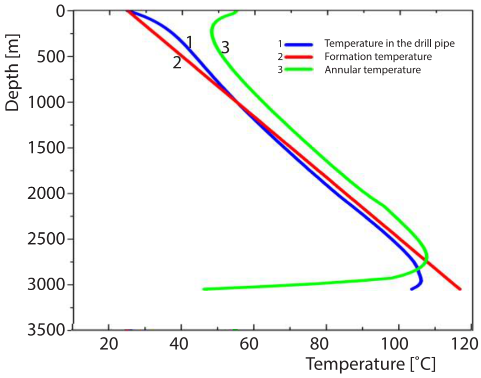

Figure 7. Model-predicted wellbore temperature profile with bit nozzle 339 mm^2

Conclusions

In this study, a temperature-pressure coupling calculation model was developed for predicting the wellbore temperature profile in gas drilling. The model was solved by cycle coupling iteration method. The following conclusions are drawn based on the analysis.

- Temperature in the pipe increases parallel with the formation temperature. At the bottom hole, under the influence of Joule-Thomson cooling effect, there is a large temperature reduction at the bit. Near the wellhead, annular temperature rises rapidly under the influence of friction heat.
- Heat source has great influence on the temperature distribution. Wellbore temperature considering the influence of heat source is higher than that without considering the influence of heat source at the same depth.
- Gas-flow rate has limited influence on the wellbore temperature except the bottom-hole temperature and wellhead temperature. Temperature ranges at the bottom hole and near the wellhead increase with the increasing gas-flow rate.
- Bit nozzle size has great influence on the temperature reduction range at the bottom hole. The smaller the bit nozzle size is, the larger the temperature reduction range is. On the other hand, after gas-flows upward a distance from the bottom-hole, the wellbore temperature tends to be same, whatever the bit nozzle size is.

Nomenclature

c_g – specific heat capacity of gas, [Jkg^{-1}°C^{-1}]
c_p – specific heat capacity of the drill pipe, [Jkg^{-1}°C^{-1}]
D_i – hydraulic radius of drill pipe, [mm]
D_o – hydraulic radius of annulus, [mm]
e – absolute roughness, [mm]
f – friction coefficient, [–]
g – gravitational acceleration, [ms^2]
g_f – the geothermal gradient, [°Cm^{-1}]
H – well depth, [m]
h_1 – convection heat transfer coefficient of the inner wall of the drill pipe, [Wm^{-2}°C^{-1}]
h_2 – convection heat transfer coefficient of the outer wall of drill pipe, [Wm^{-2}°C^{-1}]
h_3 – convection heat transfer coefficient of the wellbore wall, [Wm^{-2}°C^{-1}]
k_f – thermal conductivity of the formation, [Wm^{-1}°C^{-1}]
k_p – thermal conductivity of the drill pipe, [Wm^{-1}°C^{-1}]
k_w – thermal conductivity of borehole wall, (casing/rock), [Wm^{-1}°C^{-1}]
k' – specific heat ratio of gas, [–]
P_{dn} – pressure in the downstream of the bit, [MPa]

P_{up} – pressure in the upstream of the bit, [MPa]
Q – heat source term of unit length, [Wm^{-1}]
Q_a – energy source term of unit length in the annulus, [Wm^{-1}]
Q_p – energy source term of unit length inside the drill pipe, [Wm^{-1}]
q – gas-flow rate, [m^{3}s^{-1}]
r_1 – inner radius of the drill pipe, [m]
r_2 – outer radius of the drill pipe, [m]
r_3 – wellbore radius, [m]
r_i – radial distance in the formation, [m]
T_1 – gas temperature in the drill pipe, [°C]
T_2 – temperature of the drill pipe, [°C]
T_3 – temperature of gas in the annulus, [°C]
T_4 – borehole wall temperature, [°C]
T_{dn} – temperature in the downstream of the bit, [°C]
T_i – formation temperature, include casing, cement sheath and rock, [°C]
T_h – formation temperature far away from the welbore
T_s – surface temperature, [°C]
T_{up} – temperature in the upstream of the bit, [°C]
t – time variable, [s]
v_i – gas velocity in the drill pipe and annulus, [ms^{-1}]
v_o – gas velocity in the drill pipe and annulus, [ms^{-1}]
z – axial direction distance, [m]

Greek symbols

ρ_g – density of gas in the drill pipe, [kgm^{-3}]
ρ_{ga} – density of gas in the annulus, [kgm^{-3}]

Subscribt

i – node number of the formation in the r direction, $4 \leq i \leq 10$

Reference

[1] Ramey, H. J., Wellbore Heat Transmission, *Journal of Petroleum Technology*, *14* (2013), 4, pp. 427-435
[2] Edwardson, M. J., *et al*., Calculation of Formation Temperature Disturbances Caused by Mud Circulation, *Journal Pet Technal*, *14* (1962), 4, pp. 416-426
[3] Raymond, L. R., Temperature Distribution in a Circulating Drilling Fluid, *Journal of Petroleum Technology*, *21* (1969), 3, pp. 333-341
[4] Holmes, C. S., Swift, S. C., Calculation of Circulating Mud Temperature, *Journal of Petroleum Technol*-ogy, *22* (1960), 6, pp. 670-674
[5] Keller, H. H., *et al*., Temperature Distribution in Circulating Mud Columns, *Society of Petroleum Engineers Journal*, *13* (1973), 01, pp. 23-30
[6] Marshall, D. W., Bentsen R. G., A Computer Model to Determine the Temperature Distributions in a Wellbore, *Journal of Canadian Petroleum Technology*, *21*(1982), 1, pp. 63-75
[7] Kabir, C. S., *et al*., Determining Circulating Fluid Temperature in Drilling Workover, and Well-Control Operations, *SPE Drilling & Completion*, *11* (1996), 2, pp. 74-79
[8] Espinosa-Paredes G., *et al*., A Computer Program for Estimation of Fully Transient Temperatures in Geothermal Wells during Circulation and Shut-in, *Computers & Geosciences*, *27* (2001), 3, pp. 327-344
[9] Wu, B., *et al.*, A Coupled Model for Wellbore/Reservoir Temperature Prediction and Stress Analysis during Fluid Circulation, *Proceedings*, 46th US Rock Mechanics/Geomechanics Symposium, Chicago, Ill., USA, pp. 24-27
[10] Hasan, A. R., Kabir, C. S., Wellbore Heat Transfer Modelling and Applications, *Journal of Petroleum Science and Engineering*, *86-87* (2012), May, pp.127-136
[11] Hasan, A. R., Kabir C. S., Aspects of Wellbore Heat Transfer during Two-Phase Flow, *SPE Production & Facilities*, *9* (1994), 3, pp.11-216
[12] Zhang, H. Y., Thermal Stress Analysis on Bottom Hole Rock in Gas Drilling, *Journal of China University of Petroleum (Edition of Natural Science)*, *37* (2013), 1, pp. 70-74
[13] Yang, M., *et al.*, A Transient Heat Transfer Model of Wellbore and Formation during the Whole Drilling Process, *Acta Petrolei Sinica*, *34* (2013), 2, pp. 366-371
[14] Yang, M., *et al*., Determining Initial Formation Temperature Considering Radial Temperature Gradient and Axial Thermal Conduction of the Wellbore Fluid, *Applied Thermal Engineering*, *147* (2019), Jan., pp. 876-885
[15] Yang, H. W., *et al*., Numerical Analysis of Transient Wellbore Thermal Behavior in Dynamic Deepwater Multi-Gradient Drilling, *Energy*, *179* (2019), July, pp. 138-153
[16] Li, J., *et al*., The Complexity of Thermal Effect on Rock Failure in Gas-Drilling Shale-Gas Wells, *Journal of Natural Gas Science and Engineering*, *21* (2014), Nov., pp. 255-259
[17] Li, J., *et al*., A Closed Form Mathematical Model for Predicting Gas Temperature in Gas-Drilling Unconventional Tight Reservoirs, *Journal of Natural Gas Science and Engineering*, *27* (2015), P1, pp. 284-289

[18] Li, B., *et al*., A New Numerical Solution Predict the Temperature Profile of Gas-Hydrate-Well Drilling, *SPE Journal*, *22* (2017), 4, pp. 1201-1212
[19] Li, X. J., *et al*., A Wellbore Flow Model and Coupling Solution for Supercritical CO_2 Fracturing, *Journal of China University of Petroleum*, *42* (2018), 2, pp. 87-94
[20] Li, M. B., *et al*., Thermal Performance Analysis of Drilling Horizontal Wells in High Temperature Formations, *Applied Thermal Engineering*, *78* (2015), Mar., pp. 217-227
[21] Lienhard IV, J. H., *et al.*, *A Heat Transfer Textbook*, 3rd ed., Phlogiston Press, Cambridge, Mass., USA, 2005
[22] Incropera, F. P., *Fundamentals of Heat and Mass Transfer*, 8th ed., Wiley Press., New York, USA, 2006
[23] Guo, B. Y., *et al*., *Gas Volume Requirements for Underbalanced Drilling*, PennWell Corporation, Oklahoma, Okla., USA, 2002
[24] Li, J., *et al*., The Optimal Range of the Nitrogen-Injection Rate in Shale-Gas Well Drilling, *SPE Drilling & Completion*, *28* (2013), 1, pp. 60-64
[25] Machado, C. J., Ikoku, C. U., Experimental Determination of Solids Fraction and Minimum Volumetric Requirements in Air and Gas Drilling, *Journal of Petroleum Technology*, *34* (1982), 11, pp. 2645-2655
[26] Anderson, J., *et al*., *Fundamentals of Aerodynamics*, 5th ed., McGraw-Hill Companies, Inc., New York, USA, 2011
[27] Wang, C. X., *et al*., Hole Temperature Variation and Its Effects on Gas Injection Rate During Gas Drilling, *Natural Gas Industry*, *27* (2007), 10, pp. 67-70
[28] Ping, L. Q., The Study of Bottom-Hole Pressure Prediction Model for the Full Hole in Underbalanced Drilling, Ph. D. thesis, China University of Petroleum, Beijing, China, 2007
[29] Priscila, F. B., *et al*., Estimation of Heat Flux and Temperature Field During Drilling Process Using Dynamic Observers Based on Green's Function, *Applied Thermal Engineering*, *48* (2012), C, pp. 144-154
[30] GU, H., *et al.*, Steam Injection for Heavy Oil Recovery: Modelling of Wellbore Heat Efficiency and Analysis of Steam Injection Performance, *Energy Conversion and Management*, *97* (2015), June, pp. 166-177
[31] Xiao, J. N., *et al*., A Coupled Reservoir/Wellbore Model for Calculating Pressure and Inflow Profile A long a Horizontal Well with Stinger Completion, *Petroleum Science and Technology*, *29* (2011), 08, pp. 788-795
[32] Wang, H. Z., *et al*., Influences of Formation Water Invasion on the Wellbore Temperature and Pressure in Supercritical CO_2 Drilling, *Petroleum Exploration and Development*, *38* (2011), 3, pp. 362-368
[33] Shi, M., *et al*., A Wellbore Temperature Model and Its Parametric Sensitivity Analysis, *Journal of Southwest Petroleum Institute*, *24* (2002), 01, pp. 57-60
[34] Yang M., *et al*., A Novel Method for Estimating Transient Thermal Behavior of the Wellbore with the Drilling String Maintaining an Eccentric Position in Deep Well Operation, *Applied Thermal Engineering*, *163* (2019), 25, pp. 1-11

Paper submitted: March 14, 2020
Paper revised: Apryl 14, 2020
Paper accepted: Apryl 30, 2020