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Analysis on Influential Factors of Well Temperature for Deepwater Drilling

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Abstract
Wellbore circulating temperature must be predicted accurately to prevent gas hydrate and safe well construction operations during deepwater drilling. A model for predicting wellbore temperature distribution in deep water wells during circulation has been developed in terms of thermodynamics theory in this paper. And the influential factorsare analyzed. Model calculation results indicate that temperature profile is strongly dependent on mud specific heat and thermal conductivity, mud density and flow rate dependence of temperature effects is small. Wellbore temperature is dynamic, temperature increases with the increase of circulating time, and tend to be constant when circulating time reaches a certain value. And geothermal gradients of formation under mud line have a significant influence on wellbore temperature.

Key words: Temperature distribution; Deepwater drilling; Thermodynamics theory; Influential factors

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INTRODUCTION
The knowledge of down hole circulating temperature is essential to the design of drilling and cementing operations. During drilling operations high pressures and low fluid temperature can cause formation of gas hydrates[1]. The formation of hydrates can result in several adverse effects such as plug formation in blowout preventers and subsea wellhead[2,3]. Inadequate knowledge of the temperature regime in the wellbore during cementing operation is one cause of cement job failures[4]. The precise knowledge of heat transfer is critical in the effort to prevent gas hydrate and safe well construction operations. The main purpose of this study is to developa model for predicting the temperature distribution in a circulating well and analysis the influence factors for deepwater drilling.

1. TEMEPERATURE MODEL
Physical model for wellbore fluid flow and heat transfer in formation for deep water is shown in Figure 1. To obtain expressions for the temperature of fluid in the annulus and the drilling pipe, we set up an energy balance over a differential element of length, dz, of the annular fluid as shown in Figure 2.

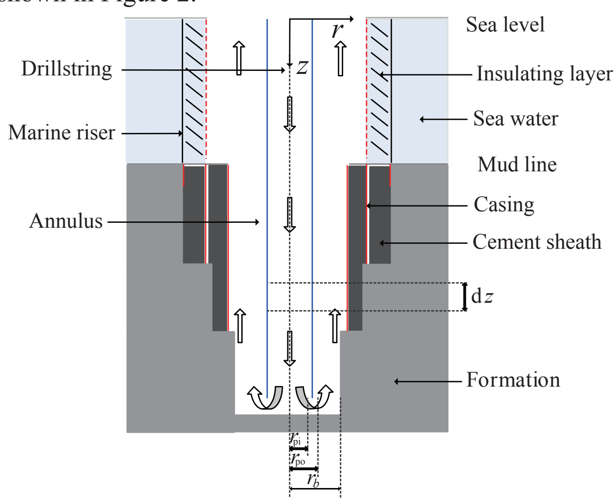

Figure 1
Physical Model for Wellbore Fluid Flow and Heat Transfer in Deep Water

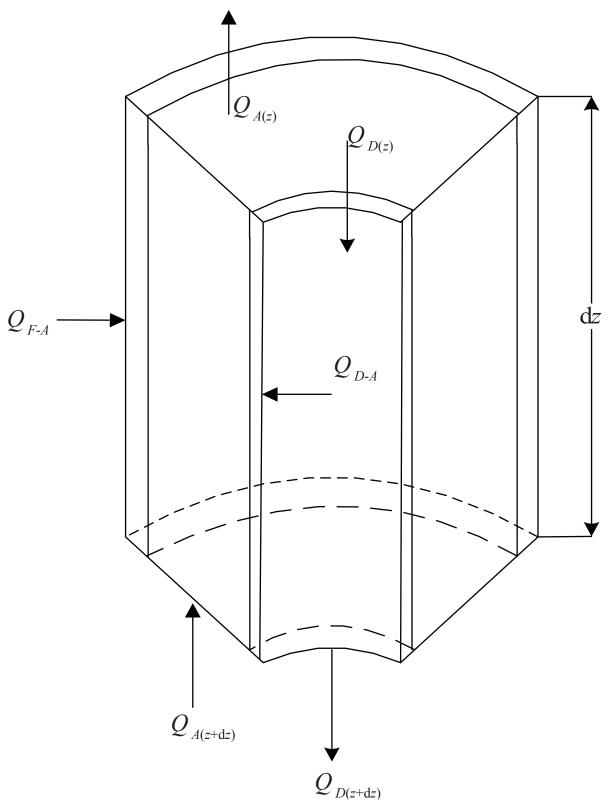

Figure 2
Differential Element for Wellbore Heat Transfer

The first law of thermodynamics applicable to a control volume shown in Figure 1 may be expressed as: Rate of accumulation of energy within control volume = Rate of energy into of control volume due to fluid flow - Rate of energy out of control volume due to fluid flow - Rate of addition of heat to control volume from its surroundings[5].

1.1 Temperature Model Above Mud Line

1.1.1 Energy Equations in Drill Pipe

Rate of energy into/out of control volume due to fluid down flow is $Q_{D(z)}$ and $Q_{D(z+dz)}$, rate of addition of heat to control volume from drill pipe inner wall is Q_{Wi-D}, and rate of accumulation of energy in drill pipe is Q_{DI}. The law of conservation of energy is given by:

$$Q_{D(z)} - Q_{D(z+dz)} + Q_{Wi-D} = Q_{DI}. \quad (1)$$

The net energy of the control volume due to drilling fluid flow down along drill pipe may be defined by[6]:

$$Q_{D(z)} - Q_{D(z+dz)} = -\rho_D \pi r_{pi}^2 v_D C_P \frac{\partial T_D(z,t)}{\partial z}. \quad (2)$$

The net energy of the control volume because of radial convective heat transfer from drill pipe inner wall can be written as follow:

$$Q_{Wi-A} = 2\pi r_{pi} h_{pi} [T_w(z,t) - TD(z,t)]. \quad (3)$$

Rate of accumulation of energy within control volume in drill pipe is given by[7]:

$$Q_{DI} = \rho_D \pi r_{pi}^2 C_P \frac{\partial T_D(z,t)}{\partial t}. \quad (4)$$

By substituting Equations (2), (3), (4) into Equation (1), energy equation in drill pipe is obtained:

$$\rho_D \pi r_{pi}^2 C_P \frac{\partial T_D(z,t)}{\partial t} + 2\pi r_{pi} h_{pi} [T_D(z,t) - T_W(z,t)] = -\rho_D \pi r_{pi}^2 C_P \frac{\partial T_D(z,t)}{\partial t}. \quad (5)$$

1.1.2 Energy Equations of Drill Pipe Wall

Drill pipe wall separates the flow in drill pipe from that in annulus. Rate of energy into/out of drill pipe wall is $Q_{W(z)}$and $Q_{W(z+dz)}$, rate of addition of heat between drill pipe inner and outer wall is Q_{Wo-Wi}, and rate of energy accumulation of drill pipe wall is Q_{WI}. The law of conservation of energy is given by:

$$Q_{W(z+dz)} - Q_{W(z)} + Q_{Wo-Wi} = Q_{WI}. \quad (6)$$

The net energy of drill pipe wall due to axial conduction of heat may be defined by:

$$Q_{W(z+dz)} - Q_{W(z)} = k_{dp} \pi \left(r_{po}^2 - r_{pi}^2\right) \frac{\partial^2 T_W(z,t)}{\partial z^2}. \quad (7)$$

The net energy of drill pipe wall because of radial convective heat transfer between inner and outer wall of drill pipe can be written as follow:

$$Q_{Wo-Wi} = 2\pi r_{po} h_{po} [T_A(z,t) - T_W(z,t)] - 2\pi r_{pi} h_{pi} [T_W(z,t) - T_D(z,t)]. \quad (8)$$

Rate of accumulation of energy within control volume of drill pipe wall is given by:

$$Q_{WI} = \rho_{dp} C_{dp} \pi \left(r_{po}^2 - r_{pi}^2\right) \frac{\partial T_W(z,t)}{\partial t}. \quad (9)$$

By substituting Equations (7), (8), (9) into Equation (4), energy equation of drill pipe wall is obtained:

$$k_{dp} \frac{\partial^2 T_W(z,t)}{\partial z^2} + \frac{2 r_{po} h_{po}}{r_{po}^2 - r_{pi}^2} [T_A(z,t) - T_W(z,t)] + \frac{2\pi r_{pi} h_{pi}}{r_{po}^2 - r_{pi}^2} [T_D(z,t) - T_W(z,t)] = \rho_{dp} C_{dp} \frac{\partial T_W(z,t)}{\partial t}. \quad (10)$$

1.1.3 Energy Equations in Annulus

In annulus, rate of energy into/out of control volume due to fluid up flow is $Q_{A(z+dz)}$ and $Q_{A(z)}$, rate of addition of heat to control volume from drill pipe outer wall is Q_{Wo-A}, rate of addition of heat to control volume from marine riser inner wall is Q_{R-A} and rate of accumulation of energy in annulus is Q_{AI}. The law of conservation of energy is given by:

$$Q_{A(z+dz)} - Q_{A(z)} + Q_{W-A} + Q_{S-A} = Q_{AI}. \quad (11)$$

The net energy of radial convective heat transfer between drill pipe outer wall and annulus fluid may be expressed as:

$$Q_{Wo-A} = 2\pi r_{po} h_{po} [T_W(z,t) - T_A(z,t)]. \quad (12)$$

The net energy of radial convective heat transfer between marine riser inner wall and annulus fluid may be defined as:

$$Q_{R-A} = 2\pi r_{ri} h_S [T_S(z,t) - T_A(z,t)]. \quad (13)$$

The net energy of the control volume due to drilling fluid flow up along drill pipe may be given by:

$$Q_{A(z+dz)} - Q_{A(z)} = \rho_A \pi \left(r_{ri}^2 - r_{po}^2\right) v_A C_P \frac{\partial T_A(z,t)}{\partial z}. \quad (14)$$

Rate of accumulation of energy within control volume in annulus is given by:

$$Q_{AI} = \rho_A \pi\left(r_{ri}^2 - r_{co}^2\right)C_P \frac{\partial T_A\left(z,t\right)}{\partial t}. \quad (15)$$

By substituting Equations (12), (13), (14), (15) into Equation (11), energy equation in annulus is obtained:

$$\rho_A \pi\left(r_{ri}^2 - r_{co}^2\right)v_A C_P \frac{\partial T_A\left(z,t\right)}{\partial z} + 2\pi r_{ri} h_S\left[T_S\left(z,t\right) - T_A\left(z,t\right)\right] + 2\pi r_{po} h_{po}\left[T_W\left(z,t\right) - T_A\left(z,t\right)\right] = \rho_A \pi\left(r_{ri}^2 - r_{co}^2\right)C_P \frac{\partial T_A\left(z,t\right)}{\partial t}. \quad (16)$$

Where ρ_A, ρ_D, ρ_{dp} are annulus fluid density, drill pipe fluid density and drill pipe density respectively, kg/m^3; v_A, v_D are fluid velocity of annulus and drill pipe respectively, m/s; C_P , C_{dp} are the specific heat of fluid and drill pipe, J/(kg·C); r_{po} is outside radius of drillpipe, m; r_{pi} is inside radius of drillpipe, m; r_{ro} is outside radius of marine riser, m; r_{ri} is inside radius of marine riser, m; k_{dp}, k_S are the conductivity of drill pipe and sea,W/(m·℃); h_{pi}, h_{po}, h_S are the convective heat transfer coefficient for annulus, drilling pipe and fluid and sea water,W/(m·℃); T_A, T_D, T_S are the temperature of annulus fluid, drill pipe fluid and sea, ℃.

Equations (5), (10) and (16) are the models of temperature distribution in wellbore above mud line, which can be calculated by numerical method.

1.2 Temperature Model Under Mud Line

1.2.1 Energy Equation in Drill Pipe

$$\rho_D \pi r_{pi}^2 v_D C_P \frac{\partial T_D\left(z,t\right)}{\partial z} + 2\pi r_{pi} h_{pi}\left[T_W\left(z,t\right) - T_D\left(z,t\right)\right] = -\rho_D \pi r_{pi}^2 C_P \frac{\partial T_D\left(z,t\right)}{\partial t}. \quad (17)$$

1.2.2 Energy Equation of Drill Pipe Wall

$$k_{dp}\frac{\partial^2 T_W\left(z,t\right)}{\partial z^2} + \frac{2 r_{po} h_{po}}{r_{po}^2 - r_{pi}^2}\left[T_A\left(z,t\right) - T_W\left(z,t\right)\right] + \frac{2\pi r_{pi} h_{pi}}{r_{po}^2 - r_{pi}^2}\left[T_D\left(z,t\right) - T_W\left(z,t\right)\right] = -\rho_{dp} C_{dp}\frac{\partial T_W\left(z,t\right)}{\partial t}. \quad (18)$$

1.2.3 Energy Equation in Annulus

In annulus, rate of energy into/out of control volume due to fluid up flow is $Q_{A(z+dz)}$ and $Q_{A(z)}$, rate of addition of heat to control volume from drill pipe outer wall is $Q_{Wo\text{-}A}$, rate of addition of heat to control volume from formation is $Q_{F\text{-}A}$ and rate of accumulation of energy in annulus is Q_{AI}. The law of conservation of energy is given by:

$$Q_{A(z+dz)} - Q_{A(z)} + Q_{W\text{-}A} + Q_{F\text{-}A} = Q_{AI}. \quad (19)$$

The net energy of radial convective heat transfer between drill pipe outer wall and annulus fluid may be expressed as:

$$Q_{Wo\text{-}A} = 2\pi r_{po} h_{po}[T_W(z,t) - T_A(z,t)]. \quad (20)$$

Heat transferred from formation to well bore/formation interface is given by:

$$Q_{F-WB} = \frac{2\pi k_F}{t_D}\left[T_F\left(z,t\right) - T_{WB}\left(z,t\right)\right]. \quad (21)$$

Heat transferred from well bore/formation interface to annulus fluid is defined by:

$$Q_{WB\text{-}A} = 2\pi r_b U_b [T_{WB}(z,t) - T_A(z,t)]. \quad (22)$$

By combining Equations (21) and (22), the net energy of radial convective heat transfer between formation and annulus fluid can be written as:

$$Q_{F\text{-}A} = \frac{2\pi k_F r_b U_b}{r_b U_b t_D + k_F}\left[T_F\left(z,t\right) - T_A\left(z,t\right)\right]. \quad (23)$$

U_b is the heat transfer coefficient of well bore/formation interface and annulus fluid, which is expressed as[8]:

$$U_b = \left[\frac{1}{h_{A\text{-}D}} + \frac{r_{po}\, ln\left(r_b / r_{po}\right)}{k_{cem}}\right]^{-1}. \quad (24)$$

t_D is dimensionless circulation time[9],

$$t_D = 1.1281\sqrt{t_{Di}}\left[1 - 0.3\sqrt{t_{Di}}\right] \quad 10^{-10} \le t_{Di} \le 1.5. \quad (25)$$

$$t_D = \left[0.4036 + 0.5\, ln\left(t_{Di}\right)\right]\left[1 + \frac{0.6}{t_{Di}}\right] \quad t_{Di} > 1.5. \quad (26)$$

$$t_{Di} = \alpha t / r_b^2 \quad \alpha = \frac{k_F}{c_F \rho_F}. \quad (27)$$

The net energy of the control volume due to drilling fluid flow up along drill pipe may be given by:

$$Q_{A(z+dz)} - Q_{A(z)} = \rho_A \pi\left(r_b^2 - r_{po}^2\right)v_A C_P \frac{\partial T_A\left(z,t\right)}{\partial z}. \quad (28)$$

Rate of accumulation of energy within control volume in annulus is given by:

$$Q_{AI} = \rho_A \pi\left(r_b^2 - r_{po}^2\right)C_P \frac{\partial T_A\left(z,t\right)}{\partial t}. \quad (29)$$

By substituting Equations (20), (23), (24), (25) into Equation (19), energy equation in annulus is obtained:

$$\rho_A \pi\left(r_b^2 - r_{po}^2\right)v_A C_P \frac{\partial T_A\left(z,t\right)}{\partial z} + \frac{2\pi k_F r_b U_b}{r_b U_b t_D + k_F}\left[T_F\left(z,t\right) - T_A\left(z,t\right)\right] + 2\pi r_{po} h_{po}\left[T_W\left(z,t\right) - T_A\left(z,t\right)\right] = \rho_A \pi\left(r_b^2 - r_{po}^2\right)C_P \frac{\partial T_A\left(z,t\right)}{\partial t} \quad (30)$$

Where c_F is the heat capacity of formation, J/(kg·C); ρ_F is formation density, kg/m^3; r_b is radius of the well bore, m; k_F, k_{cem} is conductivity of formation and cementing respectively,W/(m·℃); $h_{A\text{-}D}$ is convective heat transfer coefficient, W/(m·℃); T_{WB} is the temperature at well bore/formation interface, ℃; T_F is formation temperature, ℃.

Equations (17), (18) and (30) are the models of temperature distribution in wellbore above mud line, which can be calculated by finite difference method with initial conditions and boundary conditions.

2. MODEL SIMULATION

The computer code was subsequently employed to validate the temperature model. Parameters used for the simulations is shown in Table 1.

Table 1
Basic Data

Water depth	Well depth	Riser OD	Wellbore diameter	Drillpipe OD
1,152 m	3,000 m	501.65 mm	215.9 mm	127 mm
Circulation rate	Inlet temperature	Water temperature at surface	Water temperature at seabed	Geothermal gradient
2 m^3/min	22 ℃	23 ℃	4.34 ℃	2.5 ℃/100 m

Table 2
Physical Parameters of Mediums

Physical parameters	Drilling fluid	Drill string	Cement	Formation
Density (kg/m^3)	1,300	7,800	1,025	2,640
Specific heat [J/(kg·℃)]	1,675	400	3,890	837
Thermal conductivity [w/(m·℃)]	1.73	43.75	0.58	2.25

The effects of circulation hours, drilling fluid specific heat, thermal conductivity, density, flow rate and geothermal gradient on annulus temperature distribution are shown in Figures 3-8.

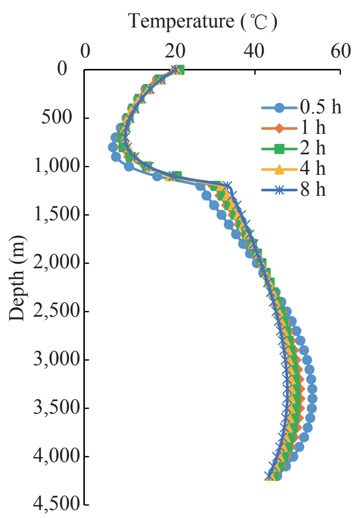

Figure 3
Temperature in Annulus With Well Depth for Different Circulation Times

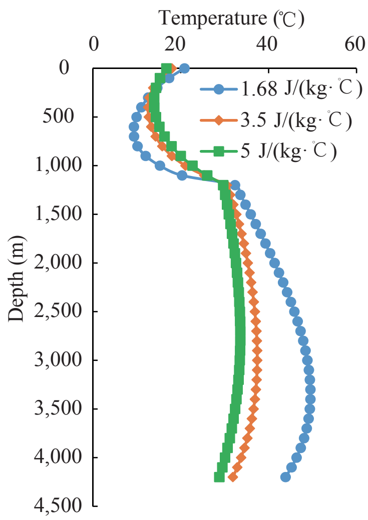

Figure 4
Temperature With Well Depth for Different Drilling Fluid Specific Heat

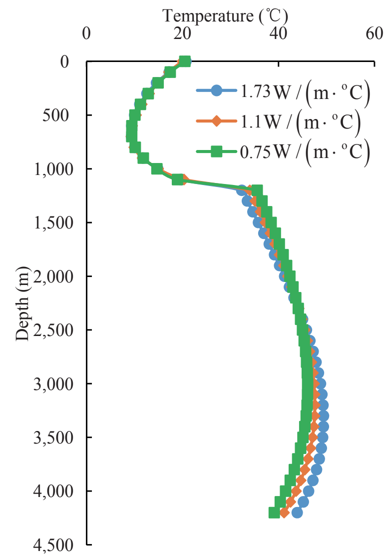

Figure 5
Temperature With Well Depth for Different Drilling Fluid Thermal Conductivity Coefficients

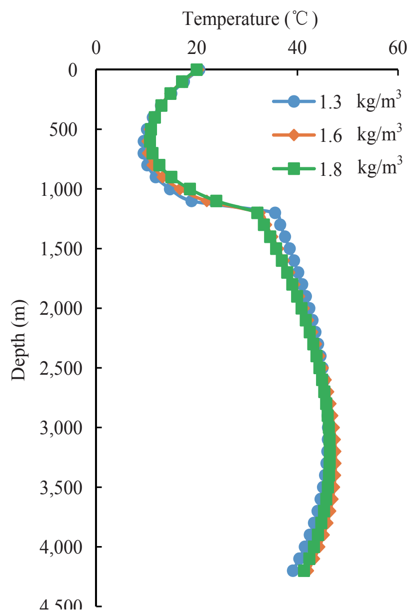

Figure 6
Temperature With Well Depth for Different Drilling Fluid Densities

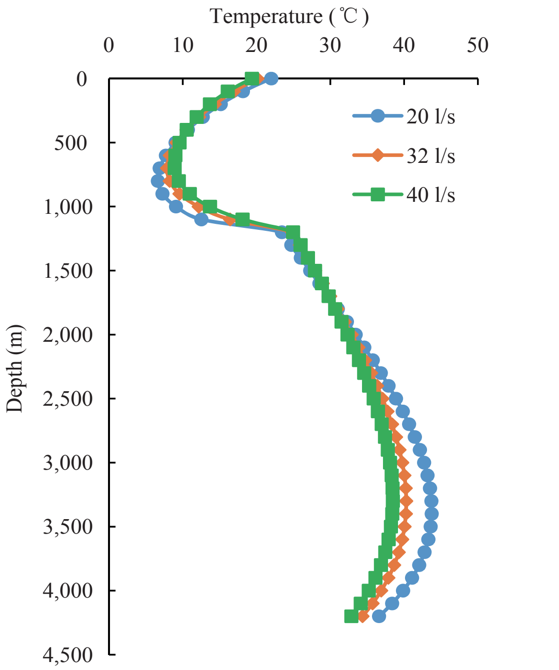

Figure 7
Temperature With Circulation Time for Different Drilling Fluid Flow Rates

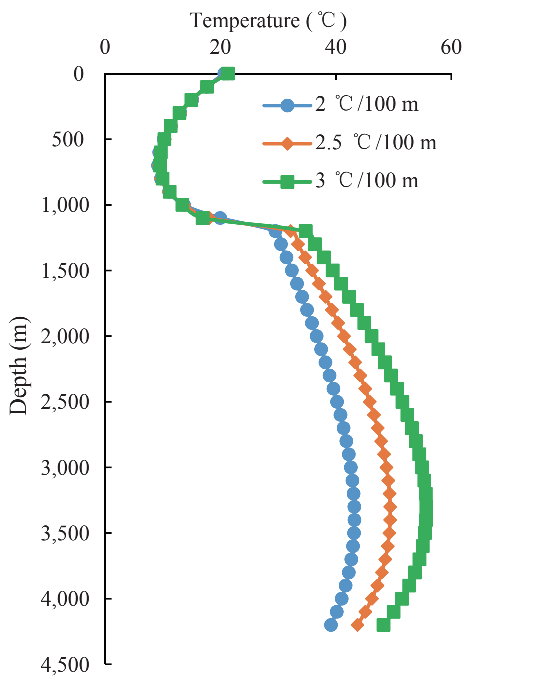

Figure 8
Temperature in Annulus With Well Depth for Different Geothermal Gradients

As seen in Figures 3-8, the influential factors of annulus temperature are presented as follow.

2.1 Circulation Time

Figure 3 shows how fluid temperature inside the annulus change with circulation times. As shown in Figure 3, circulation times has a very significant effect on annulus temperature profile. With the increasing of circulation time, temperature increases, but the degree of influence weaken gradually. When the fluid circulating 8 hours, wellbore temperature changes very show, it tend to be constant.

2.2 Drilling Fluid Specific Heat

Temperature profile is strongly dependent on mud specific heat. As shown in Figure 4, Bottom hole temperature and annulus maximum temperature decreases with the increasing of mud specific heat. The higher mud specific heat, the smaller variation range of annulus temperature. Bottom hole temperature increased 12℃with drilling fluid specific heat decreasing from 3.5 to 1.68 J/(g·℃), while it decreased 6 ℃ with drilling fluid specific heat increasing from 3.5 to 5 J/(g·℃).

2.3 Drilling Fluid Thermal Conductivity Coefficients

Temperature with well depth for different drilling fluid thermal conductivity coefficients is shown in Figure 5. Bottom hole temperature decreased 3℃ with drilling fluid thermal conductivity coefficient decreasing from 1.73 to 1.1 W/(m·℃). As shown in this figure, the large change of drilling fluid thermal conductivity can make a significant difference in annulus temperature, but the influence is less than that of specific heat.

2.4 Drilling Fluid Density

Figure 6 shows the annulus temperature under different densities. The higher the density is, the lowerbottom hole temperature will be, as shown in Figure 6.

2.5 Drilling Fluid Flow Rate

As shown in Figure 7, drilling fluid flow rate can obviously change temperature distribution in annulus. This is because when the velocity of circulation fluid decreases, the heat transfer time between circulation fluid and sea water/formation increases.

2.6 Geothermal Gradients

Geothermal gradients of formation under mud line have a significant influence on wellbore temperature. As shown in Figure 8, wellbore temperature decreases with the decrease of geothermal gradients. For deep water drilling, geothermal gradients have distinct effect on annulus temperature under mud line, while little on the temperature above mud line.

CONCLUSION

(a) Models for predicting wellbore temperature distribution in deep water wells during circulation has been developed based on the thermodynamics theory, and solved by finite difference method.

(b) Calculation results indicate that temperature profile is strongly dependent on mud specific heat and thermal conductivity, mud density and flow rate dependence of temperature effects is small. Wellbore temperature is dynamic, temperature increases with the increase of circulating time, and tend to be constant when circulating time reaches a certain value. And geothermal gradients of formation under mud line have a significant influence on wellbore temperature.

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