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Transient temperature prediction model of horizontal wells during drilling shale gas and geothermal energy

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ABSTRACT

A transient temperature prediction model was established to analyze wellbore temperature distribution of horizontal wells during drilling shale gas and geothermal energy based on unsteady two-dimensional convection-diffusion equation and the model was discretized with finite volume methods and solved by owe relaxation iteration method. The validity of the model has been verified by field temperature data. The influence of drilling parameters on temperature distribution of drilling fluid were discussed. Results indicated that the closer to the bottom of the well, the smaller the rate of change of the drilling fluid temperature with depth. The temperature of the drilling fluid at the same well depth increases with the increasing horizontal section length, drilling fluid density, geothermal gradient and vertical depth. The temperature of the upper part of the wellbore increases with the increasing circulation time and drilling displacement, and the lower part of the wellbore decreases with the increasing circulation time and drilling displacement. Drilling fluid temperature inside the drilling string decreases with the increase in viscosity. However, drilling fluid temperature inside the annulus of the upper part of the wellbore increases with the increase of the viscosity while the drilling fluid temperature of the lower part of the wellbore decreases with the increasing viscosity.

1. Introduction

The horizontal well technology has become a very mature drilling technology, and is widely used in the oil and gas industry. In recent years, applications of horizontal wells in the development of shale gas and geothermal wells (Salamy et al., 1991; Yadav et al., 2014; Stober and Bucher, 2013; Tester et al., 2006) has gained increasing attention. In horizontal well drilling, distribution of drilling fluid temperature and near-wall formation temperature have significant influence on the density and rheology of the drilling fluid and other drilling parameters. Therefore, studying temperature distribution of horizontal wells during drilling shale gas and geothermal wells is very important.

Many factors affect wellbore temperature distribution. A number of studies have focused on wellbore temperature distribution during drilling. The wellbore temperature distribution of the horizontal wells during drilling is a dynamic process that continuously change with increasing drilling fluid cycle time (Cheng et al., 2012; Santoyo et al., 2000). The longer the cycle time of the circulating drilling fluid, the lower the bottom cycle temperature. Changes in operating conditions during drilling can have significant effects on wellbore temperature distribution (Brown et al., 1996; Durrant and Thambynayagam, 1986; Hasan and Kabir, 1994). The drilling displacement of the drilling fluid has a significant influence on bottom hole temperature, and the bottom hole temperature will decrease with the increase in drilling displacement (Song and Guan, 2012). The density and rheology of the drilling fluid and wellbore temperature are interacting and influencing each other (Kabir et al., 1996; Fraas, 1989; Guo and Li, 2001). The higher the density of the circulating drilling fluid, the lower the wellbore temperature. The circulating temperature at the same well depth increases with the increase in geothermal gradient. The bottom hole temperature increase with the increasing well depth. Compared with the steady-state temperature distribution model, the transient temperature distribution model can better reflect wellbore distribution (Hasan and Kabir, 2012; Holmes and Swift, 1970; Espinosa-Paredes et al., 2001; Zhichuan, 2011).

The mainly typical temperature prediction model for oil and gas wells are summarizes in Table 1 (Ramey, 1962; Kabir et al., 1996; Emami-Meybodi et al., 2014; Ma et al., 2013; Cai and Duan, 2015; Yang et al., 2015; You et al., 2016; Mao et al., 2016).

As depicted in Table 1, a large number of fruitful studies have been conducted on the temperature field of vertical wellbores. At present, the research on the temperature field of horizontal wellbores mainly concentrates on the oil and gas production processes, such as formation heating by steam circulation, fluid intrusion and fracturing (Emami-

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Table 1
The mainly typical temperature prediction model for oil and gas wells.

Investigators	Model type	Solution	Application well
Ramey (1962)	Steady-state model	An approximate solution	Injection well
Kabir et al., 1996	Steady-state model	Analysis formula	Gas-lift well, drilling, workover, and well-control
Ma et al. (2013)	Transient model	The control volume method	Oil production wells
Emami-Meybodi et al. (2014)	Transient model	A combination of Laplace and finite Fourier cosine transforms	Steam circulation in a horizontal wellbore
Cai and Duan, 2015	Steady-state model	The finite difference method	Fracturing horizontal wells in oil reservoir
Yang et al. (2015)	Transient model	The fully implicit finite difference method	Drilling
You et al. (2016)	Transient model	The fully implicit finite difference method	In cyclic steam-injection and geothermal wells
Mao et al. (2016)	Steady-state model	The fourth-order Runge-Kutta method	Gas wells

Meybodi et al., 2014; Ma et al., 2013; Yoshioka et al., 2005; Dawkrajai et al., 2006). However, little research has been done on the wellbore temperature field during drilling horizontal wells. The finite volume method is the most effective numerical method for solving fluid flow and heat transfer problems and has been widely used. So in this paper, the finite volume method is used instead of the finite difference method for the discretization of wellbore heat transfer model (Eymard et al., 2000; Versteeg and Malalasekera, 2007; Lazarov et al., 1996; Ollivier-Gooch and Van Altena, 2002; Coudière et al., 1999; Feistauer et al., 1997a).

This study aims to investigate transient temperature model of horizontal wells during shale gas and geothermal energy. To investigate temperature distribution of horizontal wells more thoroughly, a new transient model was established and the model was discretized with the finite volume methods and solved by owe relaxation iteration method. The model is validated against the field data of the horizontal wells from Puguang oil field. The influence of density and viscosity of drilling fluid, circulation time, drilling displacement, vertical depth, geothermal gradient, and horizontal length on distribution of drilling fluid temperature in the drill string and in the annulus is analyzed. The novelty of this paper lies in the fact that the core issue studied in this paper is the wellbore heat transfer during drilling horizontal wells. The study of wellbore temperature field during drilling horizontal wells in this paper is an important exploration of horizontal well drilling technology, which has very important guiding significance for drilling horizontal well.

2. Analysis model

2.1. Physical model of heat transfer during horizontal well drilling

During drilling, the drilling fluid flows from the drill string to the drilling bit, and flows back through the annular space between the wellbore and drill string to return to the drilling fluid pond (Coudière et al., 1999). The main form of heat transfer between the drilling fluid and inner wall of the drill string is convective heat transfer, and that of the heat transfer between the drilling fluid in the annular space and outer wall of the drill string and the wellbore is convective heat transfer (Feistauer et al., 1997a; Shirdel and Sepehrnoori, 2009; Yoshioka et al., 2007). Heat transfer in horizontal wells can be divided into three sections based on its wellbore configuration as shown in Fig. 1: vertical, inclined, and horizontal sections. In the vertical section, the formation temperature increases linearly with the increase in well depth, the drilling fluid temperature in the drill string and the annulus also rapidly increases. In the inclined section, formation temperature slowly increases as the variation of the well depth, and the temperature of the drilling fluid in the drill string and annulus also slowly increases. In the horizontal section, the formation temperature does not vary with the increase in well depth, the formation temperature may have little influence on the drilling fluid temperature inside the drill string and annulus (Morton and SŪLI, 1991). The wellbore exchanges heat not only with the drilling fluid through convective heat transfer, but also with the other media in the radial and axial direction through heat conduction. The near-wall medium mainly exchanges heat in the radial and axial direction with other media through heat conduction. The tube wall exchanges heat in the radial direction with the drilling fluid through convective heat transfer and in the axial direction through heat conduction.

2.2. Mathematical model of heat transfer of horizontal wells during drilling

The following assumptions are made for the model:

① The eccentricity of the drill string and cuttings in the wellbore do not affect the temperature field;
② Due to the large curvature of the wellbore in the inclined section, the influence of the change of deviation angle on the unit volume of the finite volume method is neglected;
③ In the drilling process, the up-and-down movement of the drill string in the formation-wellbore temperature field has no effect on the formation-wellbore temperature field.
④ The drilling fluid in the drill string downward speed is positive, and the annular drilling fluid upward speed is negative, and ignores flow velocity at the wellbore bottom.
⑤ The drilling fluid flows in one dimension in the drill string and annulus.

Fig. 1 illustrates the instantaneous temperature field physical model of horizontal well formation-wellbore. According to the finite volume method, the solution is separated and divided into finite-sized discrete grids in the well depth and vertical well depth directions.

(1) Heat transfer model inside the drilling string

The heat of the fluid volume control unit inside the drilling string consists of four sections: ① heat generated by the friction loss of the drilling fluid; ② heat transport within the drilling fluid due to downflow in the drilling string in the axial direction; ③ heat transfer between the drilling fluid and inside wall of the drilling string in the radial direction; and ④ intrinsic energy change in the drilling fluid. Thus, the above model can be described by the unsteady two-dimensional convection–diffusion equation (Lazarov et al., 1996).

$$\frac{\partial(\rho_1 c_1 T_1)}{\partial t} + \frac{\partial}{\partial x}(\rho_1 c_1 u_\mathrm{p} T_1) + \frac{\partial}{\partial y}(\rho_1 c_1 v_\mathrm{p} T_1) = \frac{\partial}{\partial x}\left(\Gamma_{1x}\frac{\partial T_1}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_{1y}\frac{\partial T_1}{\partial y}\right) + S_\mathrm{p} \tag{1}$$

where $\rho_1\rho_1$ is the density of the drilling fluid inside the drilling string in kg/m^3; c_1 is the specific heat capacity of the drilling fluid inside the drilling string in J/(kg·°C) ; T_1 is the drilling fluid temperature inside the drilling string in °C; u_p is the velocity of the drilling fluid inside the drilling string in the x direction in m/s ; v_p is the velocity of the drilling fluid inside the drilling string in the y direction in m/s ; Γ_{1x} is the overall coefficient of heat transfer of the drilling fluid inside the drilling string in the x direction in W/(m^2·°C), which takes into account the thermal conductivity of the drilling fluid, the convection heat transfer coefficient between the drilling fluid and the inner wall of the drill string, and