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Hole cleaning optimization of horizontal wells with the multi-dimensional ant colony algorithm

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ABSTRACT

Horizontal wells have been widely used to exploit unconventional oil and gas reservoirs across the world. Insufficient hole cleaning has been recognized as one of the main difficulties in drilling horizontal wells. Drilling incidents caused by insufficient hole cleaning increase unproductive drilling time, induce a great amount of additional drilling costs and may even lead to the loss of the well. Drilling a well while maintaining efficient hole cleaning is a systematic process that requires various parameters to implement hole cleaning and requires cooperative effort rather than separate work. Therefore, optimizing multiple parameters to achieve the best hole cleaning effect is of great importance. However, to the author's knowledge, few research studies in this area have been undertaken. The objective of this study is to develop a new method to optimize multiple hole cleaning parameters by introducing the ant colony algorithm. The flow rate, consistency coefficient in power law model and nozzle flow area, which are three easily-adjusted parameters to control the hole cleaning on drilling site, are selected as the optimization variables. The hydraulic constraints that affect hole cleaning optimization are proposed. The mechanism and procedures of ant colony algorithm optimization are described. The practical usefulness of the developed method is demonstrated with a field example. The effect of the selected parameters on hole cleaning is analyzed, and the hole cleaning result after optimization is compared to the data before optimization. The result of the optimization shows that hole cleaning is greatly improved and all constraints are satisfied after optimization. By analyzing the optimization results, it can be concluded that the ant colony algorithm can be used to optimize the hole cleaning problem for horizontal wells. Artificial intelligence can help optimize the drilling of horizontal wells to reduce the risk of unproductive time and decrease drilling costs. The flow rate, consistency coefficient and nozzle flow area should cooperate with one another to minimize the cutting bed height while satisfying all of the constraints. Increasing the flow rate is the most efficient way to reduce the cutting bed height. Decreasing the consistency coefficient and increasing the nozzle flow area can reduce the total pressure loss and enlarge the capacity for increasing the flow rate. Increasing the pressure-bearing capacity of the system is favorable for improving the hole cleaning of horizontal wells. The cutting bed height can be further reduced and the jet velocity can be further increased when increasing the pressure-bearing capacity of the system.

1. Introduction

Horizontal wells have been widely used to exploit unconventional oil and gas reservoirs across the world (Guo et al., 2015; Chen et al., 2014; Zhao et al., 2014; Eshkalak et al., 2014). Insufficient hole cleaning has always been recognized as one of the main difficulties in drilling horizontal wells. During the past 30 years, considerable effort has been expended to solve this problem. If drill cuttings accumulate at the low side of the wellbore and form a high cutting bed, it may cause high drag and torque, fluid loss, stuck pipe, and many other problems (Xu et al., 2001a, 2001b; Ramadan et al., 2001; Duan et al., 2008; Ogunrinde and Dosunmu, 2012). The effort required to address these drilling incidents increases the unproductive drilling time, induces significant additional drilling costs and may even lead to the loss of the well.

The hole cleaning problem is affected by many controllable and uncontrollable factors. Among these, the flow rate, fluid viscosity, drill pipe rotation rate and drill bit nozzle flow area are factors that can be controlled at the well site (Adari et al., 2000; Nazari et al.,

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2010). As a systematic process, well drilling requires that all of these parameters work together rather than work separately. The drilling system has several constraints, including a limited pressure-bearing capacity and pump capacity; fixed formation fracture pressure, pore pressure and caving pressure; and specific operational requirements, such as minimum jet velocity. If any operational parameter violates any of these constraints, it may cause drilling incidents or failure of the drilling operation. For example, an increased flow rate is favorable for hole cleaning, but will probably cause the total pressure loss to increase. However, the pressure-bearing capacity of the drilling system and pump pressure capacity are limited, so the flow rate cannot be increased without limit. In addition to the flow rate, the fluid rheology and bit nozzle flow area also affect the total pressure loss. How does one cope with all of these parameters to achieve optimal hole cleaning under constrained conditions? Apparently, these parameters must cooperate and be optimized. Therefore, optimizing multiple parameters to achieve the optimal hole cleaning effect is of great importance. Although many studies (Ozbayoglu et al., 2009; Walker and Li, 2000; Li et al., 2009; Cho et al., 2000; Cheng and Wang, 2008; Okrajni and Azar, 1986; Akhshik et al., 2015; Sanchez et al., 1999; Lasen et al., 1997; Peden et al., 1990) have focused on the effect of a single parameter on hole cleaning, to the author's knowledge, limited research has been reported on the optimization of multiple hole cleaning parameters to achieve the optimal hole cleaning effect.

As an artificial intelligence algorithm, over the past 20 years, the ant colony algorithm has been developed and used in many engineering areas. It can conduct multi-parameter optimization with reliable robustness. The ant colony algorithm will be introduced in Section 3.

The objective of this study is to develop a new method to optimize multiple hole cleaning parameters by introducing the ant colony algorithm. The developed method can be used to perform optimization under various constraints and achieve the optimal value of the optimization objective (i.e., minimal cutting bed height in this study). This method can help optimize the drilling parameters at the well site and provide technical support for designing the hole cleaning parameters.

2. Hole cleaning optimization considerations

2.1. Optimization objective

When drilling a horizontal well, a cutting bed can form from the accumulation of drill cuttings at the low side of the wellbore. If the cutting bed height is very large, it can cause high drag and torque, fluid loss, stuck pipe, and many other problems, which indicates ineffective hole cleaning. If the cutting bed height is low, the hole is very clean, which indicates effective hole cleaning. Therefore, the cutting bed height can be regarded as a criterion to assess the hole cleaning of a well. The cutting bed height should be kept as low as possible to maintain safe drilling operations, which is the main objective of hole cleaning optimization. The dimensionless cutting bed height can be calculated as follows:

$$H = \frac{100T_{cb}}{D_h} \tag{1}$$

where H is the dimensionless cutting bed height, T_{cb} is the cutting bed height, and D_h is the diameter of the open hole. SI units are adopted for all variables if not specifically indicated.

The formulas for calculating the cutting bed height developed by Zhou (Zhou and Pu, 1998) and Wang (Wang et al., 1993) are combined and rearranged in the following way to include the drill pipe rotation effect:

$$\begin{aligned} T_{cb} &= 0.015D_h\left(1000\mu_e + 194.48\mu_e^{0.5}\right)(1+0.587\varepsilon)(V_{cr}-V_a) \\ &\quad + D_h\left(0.0001N^2 - 0.35468N + 0.16236N\times V_a - 0.09465N\times\varepsilon \right. \\ &\quad \left. + 0.00034N\times V_a\times\varepsilon\right)/100 \\ \mu_e &= K[(2n+1)/(3n)]^n\left(D_h-d_{po}\right)^{1-n}(12V_a)^{n-1}/1000^n \\ V_{cr} &= 40.09\left[\frac{\left(\rho_s-\rho_f\right)}{\rho_f}d_s\right]^{0.667}\left[\frac{1+0.71\theta+0.55\sin(2\theta)}{\left(\rho_f\mu_e\right)^{0.333}}\right] \end{aligned} \tag{2}$$

where μ_e is the effective viscosity, N is the rotary speed of the drill pipes in rad/min, ε is the eccentricity of the drill pipe, V_{cr} is the critical velocity above which no cutting bed forms, V_a is the average velocity, K is the consistency index, n is the flow behavior index, d_{po} is the outer diameter of the drill pipe, d_s is the diameter of the drill cuttings, ρ_s is the cuttings density, ρ_f is the fluid density, and θ is the inclination angle of the hole.

Because the dimensionless cutting bed height H varies at different hole inclination angles along the wellbore, there is a maximum dimensionless cutting bed height (MDCBH) at a given hole inclination angle. Because this MDCBH is an indicator of hole cleaning, the objective of hole cleaning optimization is to minimize the MDCBH by adjusting the influencing parameters under given constraints.

2.2. Optimization variables and constraints

In hole cleaning optimization, there are four constraints that must be considered: the maximum allowable pressure of the circulating system constraint, maximum supplying flow rate constraint, minimum jet velocity constraint and formation condition constraint.

In drilling practice, the maximum allowable pressure of the system is limited by the pump pressure capacity and the pressure-bearing capacity of the drilling equipment, especially the surface equipment. The pressure-bearing capacity of the circulating system is the maximum allowable pressure that surface equipments (e.g., drilling hose and surface pipelines) can bear. Since these surface pipelines and hoses connect the drilling pump and the drill pipes, the drilling fluid flows through these pipelines and hoses and deliver energy from the drilling pump to the drill bit and then flow back to the surface, i.e., these hoses and pipelines are under high pressure from the drilling pump. If the total pressure loss in the circulating system exceeds the pressure-bearing capacity, the surface equipment may fail to work. Therefore, the maximum allowable pressure of the system is the smaller value between the pressure-bearing capacity of the circulating system and the pump pressure capacity.

The total pressure loss in the drilling system consists of the pressure drop through the drill bit and parasitic pressure losses in the drill pipes, drill collars, annular space, and surface equipment, which can be expressed as follows:

$$\Delta p_{loss} = \Delta p_p + \Delta p_{bit} \tag{3}$$

where Δp_{loss} is the total pressure loss of the circulating system, Δp_p is the parasitic pressure loss in the system, and Δp_{bit} is the pressure drop across the drill bit. The calculations of various pressure losses, including the annular pressure loss calculation when a cutting bed exists, are shown in the Appendix.