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Propagation model with multi-boundary conditions for periodic mud pressure wave in long wellbore

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ABSTRACT

Periodic pressure waves propagating in drilling fluids along the wellbore are widely used to transmit the downhole information through the drillstring. Although various evaluation models for the wellbore and periodic pipe flows have been studied in published literature, the influence of the frequency and multi-boundary conditions on these models for the non-Newtonian drilling fluid is rarely considered. The paper presents a one-dimensional equivalent model to simulate the propagation of the periodic pressure waves in drilling fluids along the wellbore based on the assumption that the system is isothermal and the internal diameter of drillstring is a constant value. Specially, the periodic pressure waves are divided into low-frequency part (such as pump-on pulse) and high-frequency part (such as pressure wave generated by mud pulse telemetry system). The interactions of these two parts with the turbulence and Bingham fluid are investigated based on the Navier–Stokes equation for a 2D axisymmetric transient flow subjected to the five boundary conditions including the pump, air chamber, mud pulse telemetry system, drill bit and the outlet. A finite difference method with second-order accuracy is used to solve the numerical model. Experiments in the shallow and deep wells are conducted to validate the model. The simulated results are in good agreement with the experiment measurement. Finally, the influence of the frequency on pressure wave attenuation is analyzed and the result is compared with those calculated from acoustic attenuation formula. Both results show consistent trend with increasing frequency.

1. Introduction

Propagation of pressure wave in drilling fluids is widely used for transmitting information through drillstring during oil well drilling operations. Mud pulse telemetry system (MPTs) is normally used to transmit the downhole information to the surface [1]. Such information can be the directional survey data or formation data. Periodic pressure waves carrying the downhole information can be generated by MPTs located in the downhole of a well and propagate upward through the column of drilling fluid to the surface where they are detected by a pressure transducer [2]. The relative high attenuation at high frequencies severely restricts the maximum data transmission rate, especially in a long wellbore. Besides, the pressure waves might be exposed to the internal diameter of the pipes, pulsation dampeners, pump and drill bit, all of which cause a partial reflection of the pressure wave, and the reflections may significantly distort the signal received on the surface [3]. In order to

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improve the transmission rate and evaluate the weak signals acquired on the surface, it is critical to understand the transmission behavior of the periodic pressure waves in the long wellbore.

In the oil drill field, the propagation and attenuation of the low-frequency pressure wave in the long pipe has been studied based on one-dimensional (1D) model. Oliveira et al. [4–6] presented a mathematical model for predicting the pressure propagation when the drilling fluid is pumped into a closed wellbore, and noted that the model may not be applicable for the high-frequency pressure waves. Skalle et al. [7] investigated the transient pressure behavior during pump-on based on the water hammer theory. Wolski et al. [8] presented a steady-state mathematical model for Newtonian fluids to predict surge and swab pressures in open-ended drill pipes. Barabanov [9] improved the quasi-stationary friction model for the pressure wave propagating in a turbulent flow in a long oil pipeline using the Blasius friction law. However, 1D model cannot express the flow velocity profile and the frequency dependent influence of wall-viscosity.

The propagation of the high-frequency pressure wave in pipes can be described as the acoustic model [10], which assumes that there are small perturbations from a steady mean value and the axial pressure drop is small [11], and the waves can be described as sinusoidal wave whose amplitude is relevant to the travel distance. Experiments and practical applications show that the acoustic model may be used for the propagation of the mud pressure waves with "high" frequency (>10 Hz), but not suitable for "low" frequency (<1 Hz) [2]. The reason is that the wall-viscosity has significant influence on the propagation of the low-frequency pressure wave than the frequency term.

There are numerous studies on the frequency dependent impact of the wall-viscosity. Based on a two-dimensional Navier Stokes equation, Zielke [12] improved the momentum equation by relating the wall-viscosity to the instantaneous mean flow velocity as well as the past velocity change. Since the evaluation of all the historical velocity is required, the solution costs a large amount of computation time and storage space for accurate simulation of frequency dependent behavior. Suzuki et al. [13] improved the Zielke method without losing the accuracy, but it seems complicated in spite of a one-dimensional analysis. Vardy et al. [14–16] extended Zielke's approach to a turbulent flow and developed a weighting function model for high Reynolds number transient flows in smooth pipes based on the assumption that the turbulent kinematic viscosity in the core region varies linearly within the wall shear layer and the turbulent eddy viscosity is time invariant. The Vardy-Brown model requires the storage of flow variables at all previous time steps. Brunone et al. [17–19] proposed an instantaneous acceleration-based unsteady friction model, in which the unsteady viscous effects were related to the mean local and convective acceleration terms. The model has got wide applications in the water hammer due to its simplicity and ability to produce reasonable results in agreement with the experimental results. Wahba [20–23] modeled the attenuation of the non-Newtonian laminar fluid transients using a two-dimensional water hammer model which was solved by the fourth order Runge–Kutta method and central differencing.

In this paper, a new method for analyzing the propagation of the periodic mud pressure waves in a long wellbore is presented. A one-dimensional equivalent model is proposed for both low and high frequency pressure waves in long drillstring. Corresponding algorithms with the boundary conditions including mud pump, air chamber, MPTs, drill bit and the outlet are developed and solved by a finite difference method with second-order accuracy. Finally, the comparisons between the experimental and numerical results are concluded to verify the proposed approach.

The following sections of this paper are organized as bellow: The analytical model is proposed in Section 2, and then the solution algorithm is described and the multi-boundary conditions are developed in Section 3. Simulation and experimental results are provided and discussed in Section 4. Finally, the conclusion is drawn in Section 5.

2. Modeling

2.1. System description

The scheme of the drilling fluid circuit in the drill system is illustrated in Fig. 1. The drilling fluid is pumped into the drillpipe with a triplex reciprocating pump. It flows through the air chamber, MPTs, drill bit, and then returns to the ground through the annulus of the wellhead. The drilling system includes three sections of drillpipe, one section of annulus and five boundary conditions. The first section of the drillpipe, whose length is denoted as L_c, is from the pump inlet to air chamber. The second one, whose length is denoted as L_v, is from air chamber to MPTs, and the third one whose length is denoted as L_b is from the MPTs to the drill bit. The length of the annulus is denoted as L_a. The boundary conditions include the pump inlet, air chamber, MPTs, the drill bit and the outlet. The pump inlet is a constant-flow inlet, and the air chamber is used to absorb the high-frequency pressure wave generated by the displacement changes and improve the performance of the pump. The mud pressure waves are transmitted by MPTs located at the bottom of the drillstring and measured by a pressure sensor mounted on the standpipe. Thus, the downhole information is transmitted to the surface from a downhole location in the well. During drilling operation, MPTs will not work until a desired discharge is reached, and stops working after the pump stops running for a while. The flow of the drilling fluid circuit is at a steady state before MPTs works, and the periodic flow is produced in the drilling fluid circuit after MPTs works.

In this section, a mathematical model to simulate the periodic flow will be derived based on the continuity equation and the Navier–Stokes equations. In order to simply the model, the ground facilities and downhole tools are not included in the system. Also, it is assumed that the inner diameter of the pipe manifold on the ground is equal to the inner diameter of the drillstring and the drilling fluid is modeled as a Bingham fluid.