Cutting transport simulation in a horizontal borehole near tool joints

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Abstract. In the presented study, we investigated the influence of cuttings transport in a channel with variable cross-section area to determine the pressure drop and obtain preliminary data on tool joint effect on solids deposition. The influence of boundary conditions at the channel’s inlet on flow regimes was analysed. The average particle concentration over the cross-section significantly reduced due to increasing the velocity in the narrowing area on the tool joint. Behind the tool joint, particles deposition appeared due to the reverse flow, which manifested itself as a local maximum in concentration distribution along the channel. The impact of a tool joint on the pressure drop in a single-phase flow has been more pronounced if compared to one in a two-phase flow at the given conditions.

1. Introduction
Cuttings transport is one of the main issues of directional drilling, because insufficient cleaning of the borehole may result in drill-bit sticking; mud circulation loss; excessive pump loads, vibrations and torques; and reduced penetration rate. All these may lead to serious financial loses and cause sufficient accident risk [1]. Currently, there has been a significant growth in the number of studies to investigate different flow regimes and particles sedimentation in inclined annular channels for drilling muds of different rheology [2]. A wide range of the principal parameters influenced the dynamics of cuttings such as carrier and disperse phase flow rates, drill string eccentricity and its RPM, fluid and particle properties, borehole geometry and its inclination angle add additional complexity to the studies performed. The scale of the problem calls for joint theoretical and experimental investigations to be performed.

Interactions of particles with each other, wall, carrier phase, sedimentation layer, particle form and size effect and their dispersion, complex fluid rheology, unsteadiness of flow, drill string axial position changing in time and turbulence significantly complicate the theoretical description of the process. For the time being universal approaches have not been developed using computational methods. The large number of model constants and approximations require them to be tested against experimental data that are quite difficult to obtain especially if it comes to local values. Up to now, a tool joint (TJ) effect on cutting transport has never been taken into account, despite the well-known fact that joints have a significant effect on the hydrodynamic parameters and pressure drop in case of a single-phase flow [3]. This paper presents the results of our study that used numerical modeling to investigate sedimentation layer formation near a tool joint in a horizontal annular channel.
2. Problem statement and research method

Figure 1 represents the problem’s geometry. The pipe’s inner and outer diameters are 0.127 and 0.2159 meters respectively and the TJ’s diameter is 0.1683 meters. The considered flow parameters have been selected to be close to those used while actual drilling, so that Re=300, and the particle volume concentration C =0.06 (6%). The drill string axis is displaced to be near the bottom wall in a way that the eccentricity determined relative to the TJ is equal to 0.8. In our investigation, drill string rotation was not considered and the numerical modeling was performed for an unsteady 3D problem statement based on the Reynolds-averaged Navier-Stokes equations using in-house software [4].

![Figure 1. Scheme of TJ in annular channel.](image)

2.1. Mathematical model

In our investigation, we applied the Eulerian method to describe a two-phase disperse flow. The model is based on the mixture approach with an algebraic relation for the disperse phase slip velocity \( \mathbf{u}_p = \mathbf{u}_s - \mathbf{u}_f \). The mixture is considered as heterogeneous medium, where each phase occupies a part of the volume. The average values characterizing the mixture are: the mixture density \( \rho = \rho_f(1 - \alpha) + \rho_s \alpha \); the mixture mass averaged velocity \( \mathbf{u} = (\rho_f \mathbf{u}_f(1 - \alpha) + \rho_s \mathbf{u}_s \alpha)/\rho \), where \( \mathbf{u} = (u, v, w) \) and \( \alpha \) denotes the particle volume concentration. The particles are spheres with constant diameter \( d \) and density \( \rho_s \).

The carrier is a non-Newtonian fluid of Herschel-Bulkley rheology and constant density \( \rho_f \). The governing equations describing the mixture’s motion are [5]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]

\[
\rho \frac{d\mathbf{u}}{dt} = -\nabla p + \rho \mathbf{g} + \nabla \cdot (\mathbf{T}_\mu + \mathbf{T}_t + \mathbf{T}_r) \tag{2}
\]

where \( \mathbf{T}_\mu \) denotes the mixture’s viscous stress tensor, \( \mathbf{T}_t \) is the turbulent stress tensor, \( \mathbf{T}_r \) is the “diffusion” stress due to phase slip.

The equations below describe the volume particle concentration transported by the fluid and the relative particle velocity:

\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{u}_s \alpha) = 0 \tag{3}
\]

\[
\rho_s \mathbf{u}_p/\tau_s = (\rho_s - \rho)(\mathbf{g} - (\mathbf{u} \cdot \nabla)\mathbf{u}) - \frac{1-\alpha}{\alpha} \nabla p_s - \frac{1}{\alpha}(\mathbf{F}_l + \mathbf{F}_t) \tag{4}
\]

where \( \tau_s \) denotes the particle relaxation time related to drag force, \( \mathbf{F}_l \) is the lift force, \( \mathbf{F}_t \) is the force generated by turbulent pulsations, \( \mathbf{g} \) is the acceleration due to gravity, and \( p_s \) is the “particles” pressure.

2.2. Model Closure

The suggested model utilizes a phenomenological description of mixture flow, where the effect of the disperse phase is considered by introduction of mixture effective viscosity. The viscous stress tensor is expressed as \( \mathbf{T}_\mu = 2\mu[S - 1/3(\nabla \cdot \mathbf{u})I] \). Here, \( S = 0.5(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \) denotes the mixture’s deformation rate tensor, \( \mu \) is the effective viscosity coefficient, \( I \) is the unity matrix. In general, effective viscosity
depends on the concentration, shape and size of particles. The literature contains many theoretical and empirical equations to describe the viscosity of a mixture that are accurate for various concentrations of particles. For our purposes, we applied an empirical expression suggested in [6].

The turbulent characteristics of the mixture flow were determined using the single-phase two-parameter low-Reynolds-number RANS k-ω SST model. Turbulent stresses are related to the deformation velocity of an averaged mixture flow as follows:

$$ T_t = 2 \mu_t S - \frac{2}{3} k_t I, $$

where $\mu_t$ and $k_t$ denote the turbulent viscosity and the mixture’s turbulent kinetic energy. A simplified version of the model [7] was applied to model the turbulence of non-Newtonian fluid.

Particles pressure is described by the suspension balance model [8] and includes two terms related to the shear stress migration and the pressure due to permanent particles contacts. The particles stresses are important mechanisms for description particles flow in highly concentrated regions. The normal pressure due to particles continuing contacts increases rapidly when the particle concentration is close to the maximum packing limit. The contribution to the particulate pressure due to permanent particle contact is taken into account, following Johnson and Jackson [9]. The particle relaxation time $\tau_s$ takes into account particle concentration through viscosity [8]. The simplest formula to describe particles diffusion due to turbulent pulsations $F_L$ was derived from the gradient hypothesis [10]. The lateral lift forces on a dispersed particle borne by a shear flow are modeled by the following conventional expression with the lift coefficient $C_L$:

$$ F_L = C_L \rho_f \alpha \left[ u_r \times \left[ \nabla \times u_r \right] \right]. $$

Our model has been verified by experimental works for both the laminar and turbulent flows of Newtonian and non-Newtonian fluids in annular pipes. More details and description of the model and model constants can be found in [5].

### 2.3. Input data, boundary conditions and mesh generation

In our investigation, two kinds of boundary conditions (BC) were considered as input data (figure 2). In the case of BC1 it was a steady-flow velocity profile in a channel without tool joints and particles. The profile of particle concentration was considered constant. Such a problem statement has a practical meaning as the mixture can be regarded as homogenized near drill-bit (figure 2a).

![Figure 2. Boundary conditions BC1 (a) and BC2 (b).](image-url)
To reduce the required computation time, we also applied the boundary conditions obtained from 2D computations for a steady flow of a mixture in a channel with constant cross-section and well-formed sedimentation layer that is noted here as BC2 (figure 2b). Preliminary calculations to verify meshes convergence have been performed. Figure 3 demonstrates that the ripples which are visible on concentration curves reduce as spatial resolution increases. The computation results demonstrate that formation of steady-state sedimentation layer downstream requires at least 100 hydraulic diameters (Dh). For that reason, in our study, two TJ positions were considered: at the distance Zj1=0.3 and Zj2=1.3 meters from the channel’s inlet (figure 3b), which is 3.4 and 14.6 Dh respectively. Comparison of the computation results against those obtained for full 3D statement confirmed that it is proper to use the BC2 conditions for relatively long channels.

![Figure 3](image)

**Figure 3.** Distribution of mean particle concentration in section along the annular channel: (a) without TJ; (b) with TJ. BC1 boundary condition.

3. Results and discussion

The performed numerical experiments allowed us to investigate the TJ effect on the hydrodynamic parameters of the flow and on the sedimentary layer. All figures below present the results with BC2 conditions.

Figure 4 compares the velocity fields near TJ with and without cuttings transport. In the given flow conditions, a weak reverse flow is formed behind the TJ. Figure 5 shows the particle concentration distribution in different cross-sections of the channel. Sedimentation layer slightly decreases due to increasing of flow velocity on tool joint that led to reduced mean particle concentration in a section. It is noteworthy, that the zone of reduced particle concentration starts at a certain distance before the TJ (figure 6c). A local maximum in the distribution of the mean particle concentration in section (figure 6) is observed in the expansion zone of tool joint.
Figure 4. Velocity field in the axial section $Y=0\text{m}$, BC2: (a) single-phase flow, (b) two-phase flow.

Figure 5. Particle concentration distribution in sections: (a), (b), (c), (d), (e).

In the case of single-phase flow, the mean velocity at the TJ is determined by the channel’s cross-section. The calculations show that the presence of cuttings affect the way the velocity changed on the TJ. In this case, the work area for the flow over the sedimentation layer was no longer proportional to the geometrical area of TJ. The calculations show that despite TJ position and boundary condition type (figures 3b and 6), sedimentation process behind the TJ is analogous to that in annulus channel without TJ.
Cuttings transport is an energy-consuming process, which is confirmed by the pressure distribution shown in figure 7. It is noteworthy, that the relative TJ effect on pressure drop for the single-phase flow is higher than for the two-phase one. While drilling, one normally uses pipes of more than 4.572 meter in length. Since the flow becomes steady behind the TJ at the distance that is much less than the mentioned 4.572 meter, it turns out to be very easy to estimate the full pressure drop in the borehole. All you need to know is how to determine the pressure drop for a single segment of a pipe.

4. Conclusions
In the presented study, a mathematical model and a methodology of cuttings transport numerical simulation in a channel with variable cross-section have been tested. The effect of input boundary conditions and TJ positioning on sedimentation layer formation has been estimated and the first data describing TJ effect on a sedimentation layer has been obtained. TJ effect on pressure drop for two-phase flow has been considered as well and the results obtained have been compared against those for a single-phase flow. Recommendations on determining full pressure drop in a borehole for a given drilling mode are suggested.

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