On the modes of cuttings transport in an inclined annular channel

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Abstract. The paper presents the results of the simulation of cuttings transport (solid spherical particles) by water through a long annular axisymmetric inclined channel. At the inlet uniform distribution of particles and fluid velocity was set. Inclination angle varied from 0 to 90 degrees. Modes of stationary and moving dunes and their transition into wave-shaped and stationary sediment were observed. Moving dunes could oscillate laterally and did not form a crest that occupied the entire width of the channel. In this case, dense sediment formed an S-shaped path, moving along the stream. Despite the general downstream movement of the S-shaped track (dune), a downward flow might occur in the low area with high concentration. Five basic flow regimes were identified: constant sediment, moving wave-like sediment, separated stationary dunes, S-shaped sediment and homogeneous flow. The basic flow pattern could be complicated by lateral motion and backward flow in a region of high concentration. A variant of the flow pattern map is suggested.

1. Introduction

Cuttings transport is essential while drilling. Rock crushed by bit is transported through the annular channel formed by a drilling column and the walls of a well. The process of particles transfer may be significantly non-stationary and depends on many parameters such as the flow rate of the drilling fluid, its rheological properties, the drilling speed (particles inflow), the inclination of the borehole, etc. The most problematic are the angles of inclination of 30-60 degrees from the vertical when the flow of the mixture becomes unstable [1, 2], dunes are formed [3, 4] and a backward flow appears [5]. Such regimes are characterized by a high average concentration of cuttings particles in the channel, which can lead to a stop of drilling. A correct choice of drilling regime ensures well stability and cost-effective speed of penetration.

There are a number of experimental and numerical works devoted to cuttings transport in annular channels. The problem has a large number of parameters making it very difficult to cover the entire range of drilling regimes. Typical drilling fluids are opaque, visualization is sometimes impossible, and pattern mapping is complicated. Numerical studies are sometimes carried out using commercial packages, whose models do not include all the physical processes essential for these flow regimes. Another problem has been the absence of unambiguous established terminology for description of flow
regimes in the annular channel. For the time being, the number of the modes suggested in the literature [3, 4, 6] varies from 4 to 6.

This paper describes modeling of the modes whose parameters are close to drilling regimes with the purpose to study cuttings transport and produce a flow pattern map. While modeling we studied such parameters as drilling mud flow rate (velocity) and well inclination. Such parameters as eccentricity and inner-cylinder (drill string) rotation were neglected.

2. Model description

An Eulerian approach based on the local-equilibrium mixture model [7] was applied to describe flows of solid-liquid suspensions. The mixture flow characterized by average values: mixture density is \( \rho = \rho_f (1 - \alpha) + \rho_s \alpha \), mixture mass averaged velocity is \( \rho \mathbf{u} = \rho_f \mathbf{u}_f (1 - \alpha) + \rho_s \mathbf{u}_s \alpha \), where \( \mathbf{u} = (u, v, w) \). The disperse phase slip velocity is \( \mathbf{u}_r = \mathbf{u}_s - \mathbf{u}_f \) [7, 8]. The equations describe the mixture flow:

mixture mass balance
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

mixtures momentum
\[
\rho \frac{d \mathbf{u}}{dt} = -\nabla p + \rho \mathbf{g} + \nabla \cdot (T_\mu + T_t + T_r)
\]

concentration transfer
\[
\frac{\partial \rho_s \alpha}{\partial t} + \nabla \cdot (\rho_s \alpha \mathbf{u}_s) = 0
\]

slip or relative velocity
\[
\rho_s \mathbf{u}_r = \tau_s (\rho_s - \rho)(\mathbf{g} - (\nabla \cdot \mathbf{u})\mathbf{u}) - \tau_s \frac{1 - \alpha}{\alpha} \nabla p_s - \frac{\tau_s}{\alpha} (F_L + F_t),
\]

where \( T_\mu \) denotes the mixture viscous stress tensor, \( T_t \) is the turbulent stress tensor, \( T_r \) - “diffusion” stress due to the phase slip
\[
T_r = -\frac{(1 - \alpha) \alpha \rho f \rho s}{\rho} \mathbf{u}_r \mathbf{u}_r
\]

\( \tau_s \) is a particles relaxation time related to drag force, \( F_L \) is the lift force, \( F_t \) is the force generated by turbulent particles diffusion, \( \mathbf{g} \) is the acceleration due to gravity, and \( \mathbf{p}, \mathbf{p}_s \) are mixture and particles pressures.

The suggested model utilizes a phenomenological description of mixture flow, where the effect of the disperse phase is considered by introduction the mixture effective viscosity. Viscous stress tensor is expressed as \( T_\mu = 2\mu [S - 1/3 (\nabla \cdot \mathbf{u}) \mathbf{I}] \). Here, \( S = 0.5(\nabla \mathbf{u} + \nabla \mathbf{u}^T) \) denotes the mixture deformation rate tensor, \( \mu \) is the effective viscosity coefficient, \( \mathbf{I} \) is a unity matrix. In general, the 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 the viscosity of the mixture, an empirical expression was used [9]:
\[
\mu = \left( \frac{k_y \mathbf{v}^{n-1} + \tau_y / \mathbf{v}}{\mu_f} \right) \exp \left( \frac{2.5}{\beta} \left( \frac{1}{(1 - \alpha)^{1.5} - 1} \right) \right) + \frac{\mu_0 f r P_{fr} / \mathbf{v}}{\mu_f}.
\]
The carrier’s viscosity where \( \mu_f \) defined by Herschel-Bulkley law, \( k_y \) denotes the consistency factor, \( n \) is the power index, \( \tau_y \) is the yield stress value. Relative apparent viscosity coefficient is \( \mu_r \), the model coefficient \( \beta = 1.5 \) corresponds to spherical particles. Additional viscosity \( \mu_{fr} \) corresponds to a friction in the case of permanent particles contact, here \( p_{fr} \) is the particulate pressure due to permanent contact of particles, \( \mu_{0,fr} = 0.32 \) is an empirical parameter. The mixture effective shear rate velocity \( \gamma \) is determined in (8).

The turbulent characteristics of the mixture flow were determined using the single-phase two-parameter low-Reynolds-number RANS k-\( \omega \) SST model [10]. Turbulent stresses are related to the deformation velocity of an averaged mixture flow as follows:

\[
T_t = 2\mu_t S - \frac{2}{3} k_t l
\]  
(7)

where \( \mu_t \) and \( k_t \) denote the turbulent viscosity and mixture turbulent kinetic energy respectively.

To model the turbulence in non-Newtonian fluids, a simplified version of the model [11] was applied. In the simplified model the apparent viscosity (effective viscosity) is calculated using the averaged shear rate \( \gamma \):

\[
\gamma = \frac{\mu_r}{1 - \alpha} (2S_{ij}S_{ij} + \rho \varepsilon / \mu)
\]  
(8)

where \( \varepsilon \) is the dissipation rate of the kinetic energy of the mixture turbulence.

Particles pressure \( p_s \) is described by suspension balance model (SBM) [12] and includes the two terms. The particles migration is induced by particle pressure \( p_m \) [13] and the second term \( p_{fr} \) is the particulate pressure due to permanent contact of particles [14]:

\[
p_s = \frac{(\mu_r - (1 + 2.5\alpha))\mu_f \gamma + Fr \max(\alpha - \alpha_{min}, 0)^2}{p_m} \left( \frac{\alpha_{max} - \alpha}{p_{fr}} \right)^5
\]  
(9)

where \( Fr = 0.05 \) Pa and \( \alpha_{min} = 0.5 \) are two empirical parameters, \( \alpha_{max} = 0.62 \) denotes maximum packing.

To describe particles diffusion due to turbulent pulsations we used the simplest formula derived from the gradient hypothesis and is expressed as [7, 15]:

\[
F_t = -\frac{\rho_s \mu_t}{\tau_p \rho \sigma_t} \frac{\nabla \alpha}{1 - \alpha}
\]  
(10)

here Schmidt number \( \sigma_t = 0.7 \).

The particles relaxation time \( \tau_s \) includes effect of concentration using the hindered settling function [16, 12]:

\[
\tau_s = 4 \frac{d_s}{3 C_D |\mathbf{u}_r|} \frac{\rho_s \mu_f}{\mu} \left[ \frac{\mu}{\rho_f} \right] \left[ \frac{\mu}{\rho_f} \right]
\]  
(11)

Here drag force coefficient \( C_D \) for a single spherical particle in unbounded shear flow of Herschel-Bulkley fluid [17, 18].

The lift force acting on a particle in shear flow modelled by the following conventional expression with the lift coefficient \( C_L \):

\[
F_L = C_L \rho_f \alpha \left[ \mathbf{u}_r \times \left( \nabla \times \mathbf{u}_f \right) \right]
\]  
(12)
Three-dimensional flow around steadily moving sphere in a viscous linear shear flow was studied numerically [19]. Their model can be expressed as:

\[ C_L = \sqrt{C_{L,\text{LowRe}}^2 + C_{L,\text{HighRe}}^2} \]  

(13)

where the first term accounts for the lift coefficient from low to moderate Reynolds numbers (0.01 < \text{Re}_p < 10) and the second term accounts for the lift coefficient for moderate to high Reynolds number (0.1 < \text{Re}_p < 500). Formula (13) is used in current study. In all the simulations, lift force coefficient has been upper bounded by the value of \( C_L = 0.15 \).

3. Problem statement and numerical algorithm

A flow in a long axisymmetric annular channel with an axisymmetric inner cylinder was modeled. The channel outer and inner diameters were 0.203 m (8\") and 0.114 m (4.5\"), respectively. The water rate was selected to be 0.0126 and 0.0347 m³/s (average velocity of ~0.57, 1.56 m/s or 756, 2080 l/min, respectively). The Reynolds numbers corresponding to these rates were ~34·10³ and 92·10³, respectively. The particles rate was 1.23·10⁻⁴ m³/s (ROP ~ 13.5 m/h) at the density of 2667 kg/m³ and diameter of 3 mm. The channel inclination could change from vertical (0\°) to horizontal (90\°). In order to obtain developed flow and particle distribution along the channel, after a set of numerical experiments its length was selected to be 20 m or 225 hydrodynamic diameters of the annular channel.

At the inlet uniform distribution of particles and fluid (water) velocity were set. At the outlet zero gradient for all variables was used. On the outer and inner cylinder (wall of the borehole and drill pipe) non-slip boundary condition was used. Length of simulated channel in 20 meters was chosen to achieve fully developed flow. High Reynolds number force us to use wall functions near the walls. In all simulated cases \( y^+ \) for first wall cells is more than 20.

In-house CFD code based on "σ-Flow" [20] package was used to carry out the simulations. Transport equations convective terms are approximated using the second-order upwind total variation diminishing (TVD) scheme. The velocity and pressure fields are coupled to provide satisfaction of the continuity equation using the SIMPLE-C algorithm on mutually spaced grids. Pressure field oscillations are eliminated using the Rhie–Chow method involving the special interpolation of the velocity vector at the face of control volumes. The systems of algebraic equations resulting from discretization of the original differential equations are solved iteratively using an algebraic multigrid solver. Maximum time step corresponds to CFL~1.2. Mesh resolution was chosen dense enough to simulate all features of dunes flow.

4. Results and discussion

The performed modeling has made it possible to determine flow patterns, identify their similarities and break them into types. The flow pattern map is presented in Table 1.

| Incl. \ Vel. | 0.57 m/s | 1.56 m/s |
|-------------|-----------|-----------|
| 0           | HF        | HF        |
| 5           | SS+BF     | CS+BF     |
| 15          | SS+BF     | SSD+BF    |
| 30          | SS+BF     | SSD+BF    |
| 45          | SS/WM+BF  | SS+BF     |
| 55          | WS+BF     | SS+BF     |
| 60          | WS/CS+BF  | WMS/CS+BF |
| 75          | CS+BF     | CS+BF     |
| 90          | CS        | CS        |
In total, five flow modes were identified: homogeneous flow (HF); S-shaped sediment (SS); separated stationary dunes (SSD); wave-like moving sediment (WMS); and constant sediment (CS). Flow structure can be complicated by backward flow (reverse flow or backward sliding - BF).

Figure 1. Dimensionless distribution of fluid, particles and particles distribution.

At small degrees of inclination from vertical, the effect of gravity force on particle distribution was insignificant unlike that of lift force and interparticle interaction. The lift force "pushed" the particles away from the channel walls, forming the mixture local concentration and axial velocity maxima (Fig. 1). A similar effect has been observed in pipes [21]. It is noteworthy that these two kinds of maxima had different positions, so the velocity maxima had formed in areas of low concentration where the particles exhibited the lowest resistance to the flowing water.

Figure 2. Channel bottom view: a – particle concentration distribution; b – isosurface of the suspension negative axial velocity (U = 0.57 m/s, inclination 5°).

Further increase of the inclination angle led to sedimentation of the particles of the channel walls. The sediment started to appear at 5°, while its integral value was not high and constituted only a few percent, it was enough to trigger a small zone of backward sliding (reversed flow) (Fig. 2b). At low fluid rates the sediment became unsteady and S-shaped (SS). If the fluid rate increased, the sediment transverse instability increased further at high inclination angles (see Tab. 1). For the inclination angle of 5° the flow formed steady sediment.
Further increase of the inclination angle at low fluid rate resulted in the increase of average particle concentration while the pattern preserved its characteristic S-shaped form (see Fig. 3, 4a). It is a common case that it becomes impossible for one to fully visualize a flow during an experiment, so the mode shown in Fig. 4a is characterized as separated moving dunes [6]. The effect of transverse oscillations had been reduced and become almost unseen at the flow rate of 0.57 m/s, when the particles started forming the wave-like moving sediment (WMS), which became stationary with a further increase in the inclination angle. It is worthy to mention that the reverse-flow area also reduced as the inclination angle exceeded 60°.

Figure 3. Channel bottom view: a – particle concentration distribution; b – isosurface of the suspension negative axial velocity (U = 0.57 m/s, inclination 15°).

Figure 4. Channel side view, particle concentration distribution: a – inclination 30°, b – inclination 45° (U = 0.57 m/s).

Figure 5. Channel side view, particle concentration distribution: a – inclination 55°, b – inclination 60° (U = 0.57 m/s).
At high fluid rate (1.56 m/s) and at the inclination angles of 15-30° the particles formed separated stationary transversely unstable dunes. Being separated the dunes separate the reverse flow areas, so the particles circulated inside those dunes, following the flow in its upper part and traveling downward the dune in the areas with high particle concentration. The bottom view demonstrates how the dune cross-section is distorted by flowing S-shaped sediment.

**Figure 6.** Channel bottom and side view, particle concentration distribution: a – side view; b – bottom view; c – isosurface of the suspension negative axial velocity (U = 1.56 m/s, inclination 30°).

**Conclusions**

The performed simulation of cutting transport by water along an annular channel without eccentricity and inner - cylinder rotation has made it possible to analyze the flow structure depending on the channel inclination angle and flow rate and build a flow pattern map.

It has been demonstrated that at small inclination angles the flow is characterized by almost homogeneous particle distribution along the channel cross-section with the local fluid velocity and particle concentration maxima registered near the channel walls (Sergé and Silberberg effect).

Within the range of 5-55° the particles form S-shaped sediment, single-standing stationary dunes and wave-like sediment.

At the angle over 60°, the sediment becomes almost stationary.

All the modes, apart from the vertical and horizontal ones have the reverse flow registered in the area of high particle concentration.

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