# Introduction

## Cuttings transport in petroleum drilling

In petroleum drilling, a mechanical drill bit cuts the formation into so-called cuttings. To ensure continuous operation, adequate transport of all cuttings out of the well, also referred to as hole cleaning, is critical. Transport of the solid particles out of the wellbore is principally achieved by pumping a drilling fluid into the well which continuously flushes (and cools) the drill bit and picks up the cuttings. The drilling fluid is pumped down in a central pile which is either the drill string consisting of mechanical connected drill string elements or coiled tubing. At the bit, the fluid runs through a set of nozzles. And flushes as well as cools the drill bits cutting blades. The return path of the drilling fluid and the solids is the annulus, i.e. the annular gap between the drill pipe and the outer wall. The solids are flushed and transported through the annulus back to the surface where they are separated from the drilling fluid. After some time, the drilling fluid is then recirculated into the well.

Due to the three-dimensional wellbore trajectory the drill pipes position relative to the annulus is typically off-centric. Using a coordinate system as depicted in , one may locally distinguish between a vertical and horizontal eccentricity.

Depending on the type of drilling the drill pipe may be rotating or not. In conventional drilling, the drill bit is driven by the rotating drill pipe which itself is driven by a motor at the top. In coiled tubing operations, the drill bit is typically driven by a downhole mud motor and the drill pipe does it not rotate. In case of rotation, and as a consequence of

the compliance of the segmented drill pipe system

the damping due to viscous and coulomb forces

the 3D trajectory of the wellbore and the corresponding eccentricities and interactions of the drill pipe and the outer wall

the drill pipe mostly features additional lateral motion, such as forward or backward whirling or more chaotic lateral oscillating motions. These lead These motions are I won to heavily influence cuttings transport

Outer wall may be the borehole wall or casing. From time to time, metal casing is cemented into the borehole in oder to mechanically stabilize the wellbore and prevent influx of drilling fluid or loss of drilling fluid into formation. As the wellbores depth and distance increases, smaller and smaller casings are used and hence the well bores outer diameter decreases with depth and distance.

Inadequate cuttings transport leads to insufficient hole cleaning with potentially severe consequences. Damaged and/or lost equipment, broken formation, leads to well downtime and increased costs.

The quality of solids transport throughout the wellbore back to the surface depends on many, not necessarily independent, parameters. The cuttings have to be transported by the drilling fluid over very long distances and against gravity. Many parameters mentioned previously are not constant along the wellbore path, which is why the probability that a concrete part of the well is sufficiently clean also varies along the wellbore path. For cuttings transport modelling, it is therefore crucial to identify the critical part of the wellbore where cuttings are not adequately transported and accumulated instead. In other words, in order to make a statement about hole cleaning, the definition of which is a sufficiently clean wellbore to ensure continuous operations, one needs to quantitatively investigate cuttings transport in individual parts and then aggregate this information to a global scale.

The transported solids vary significantly in size. They may be as large as 40 and as small as 0.001 mm and typically all sizes are coexisting in the well. However, the size distribution is not constant because the rotating and whirling drill pipe as well as the mechanical interaction of the cuttings itself lead to abrasive wear and shift the distribution towards smaller sizes the longer the solids are transported.

Shape

Fluid

Carrying capacity

Hole cleaning capacity

Cuttings lifting capacity

## Modeling approaches

Historically, cuttings transport modelling considered a small part off the wellbore only. Moreover, only one-dimensional (1D) modelling was performed, where the 3D Was simplified by averaging over the cross-sectional area and hence only the x-direction was considered. With recent developments in computational power, these days cuttings transport modeling has diversified and may be categorized as depicted in Figure xx.

Computationally cheap and thus fast—potentially Real-Time (RT)—computing approaches are used to simulate wellbore elements or even the wellbore in its entirety. However, many of these models are still of 1D nature and heavily rely on empirical closures and/or closure laws derived from more sophisticated modeling approaches by e.g. averaging or model order reduction (MOR) techniques. The basis of these models may be of numerical or experimental nature. In the latter case, techniques such as response surface analysis (RSA) and Design of Experiments (DoE), for instance based on multidimensional fit functions derived by means of dimensional analysis (DA), may be used to establish a process relationship in the form of an empirical correlation.

At the other end of the modeling spectrum, at the lower level of figure xx, 3D modeling approaches enable a much more detailed analysis of the physical problem. Experimental work typically involves a flow loop, where drilling fluid (model) systems are circulated and the transport of solids may be studied in detail (in a pipe or annular test section, which may even be inclined and in the case of an annular geometry, the inner pipe may be rotating). Technical developments in Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) have led to increasingly more experimental studies using translucent fluids and providing insight information of the complex fluid-solid interactions. Numerical 3D modeling by applying Computational Fluid Dynamics (CFD) is typically done with a Reynolds-Averaging approach, where the governing equations of fluid flow are ensemble-averaged to handle the phenomenon of turbulence in a comparatively computationally cheap manner. Various modeling techniques exist, the most realistic ones are based on Eulerian-Lagrangian concepts, where the fluid as the first phase is treated as a continuum and the dispersed solid particles are followed individually in a Lagrangian manner and are subject to Newton’s second law of motion. However, for larger systems this modeling approach leads to severe computational expenses. In this study, the Eulerian-Eulerian concept has been mostly used, where the solids as the dispersed phase are treated as a second continuum. CFD nature

## State of the art

## Continuum description of dense two-phase flow

# Relevant parameters, dimensional analysis and scaling

Busch et al. - 2018 - Cuttings Transport Modeling - Part 1 Specificatio

Busch et al. - 2016 - Cuttings Transport Modeling - Part 1 Specificatio

Busch and Johansen - 2019 - Cuttings Transport Modeling - Part 2 Dimensional

# Simple transient 1D model

# Rheological properties and description of drilling fluid model systems

Busch et al. - 2018 - Rheological characterization of Polyanionic Cellul

Busch and Johansen - 2018 - Judging the Generalized Newtonian Fluid assumption

# Rheological description of dense granular flow and sediment bed morphodynamics

Busch et al. - 2017 - A 2D sediment bed morphodynamics model for turbule

Busch and Johansen - 2019 - On The Validity Of The Two-Fluid-KTGF Approach For

# Modeling of turbulence

Busch et al. - 2019 - DNS vs. RANS turbulence modeling of turbulent pipe

Manuscript on Reynolds number regime (transform presentation into mansucript)

Khatibi et al. - 2017 - Investigation of Suspended Particles Around an Obs

# Trajectory of a single particle in orthogonal shear flow

Zoric et al. - 2015 - On Pragmatism in industrial modeling - Part II Wo

Busch and Johansen - 2017 - Implementation and validation of a DPM model accou

Busch and Johansen - 2018 - An Eulerian-Lagrangian CFD study of a particle set

# The effect of drill pipe rotation and lateral motion on cuttings transport

Busch and Johansen - 2019 - Cuttings transport On the coupled effect of drill