Cuttings-Transport Modeling–Part 1: Specification of Benchmark Parameters With a Norwegian-Continental-Shelf Perspective

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Summary

In oil and gas drilling, cuttings-transport-related problems are a major contributor to well downtime and costs. As a result, solutions to these problems have been extensively researched over the years, both experimentally and through simulation. Numerous review articles exist, summarizing not only the research history but also the qualitative effect of individual case parameters such as pump-flow rate, pipe rotation, and rate of penetration (ROP) on cuttings transport. However, comparing different studies is challenging because there is no common reference defined in the form of a typical and representative set of case parameters.

To develop relevant and accurate cutting-transport models, it is critical that both experiments and models are targeting flow cases relevant for respective drilling operations. Development of a clear understanding of the industrial-parameter space, as well as establishing benchmarks, will help achieve a more-concerted effort in development of models and corresponding laboratory experiments.

Other industries have established research benchmarks, such as the "NREL offshore 5-MW baseline wind turbine" (Jonkman et al. 2009) in wind-power research, providing a standardized set of case parameters and profiles, readily available for use to researchers worldwide, and resulting in straightforward benchmarking and validation as well as faster establishment of projects.

For application to the modeling of cuttings-transport phenomena, we propose a methodology for deriving a well-defined and standardized set of geometrical, operational, and environmental case parameters describing various operating points of drilling operations and procedures as well as simplified problems. The methodology is exemplified with an 8.5-in.-section drilling-ahead use case with aggregated wellbore data from the Norwegian Petroleum Directorate (NPD). The relevance and application of the derived parameters are briefly discussed in light of modeling, both experimentally and through simulations. Applying this methodology before any cuttings-transport study may enable a better definition of industry-relevant case parameters.

In Part 2, we will apply and discuss the derived parameter sets in the context of nondimensional numbers for assessment of scalability.

Introduction

The study of hole cleaning has been a major concern for several decades in the drilling industry. Inadequate hole cleaning can lead to stuck pipe, fractured formation, high rotational torque, premature bit wear, and decreased ROP, and can further cause problems during logging, casing, and cementing operations. It was reported that 70% of lost time in drilling was associated with stuck pipe (Massie et al. 1995) and one-third of the stuck-pipe problems were caused by inadequate hole cleaning (Hopkins and Leicksenring 1995).

Wellbore inclination can significantly influence cuttings-transport efficiency. During drilling, the rate of buildup of cuttings concentration in the wellbore changes gradually when the inclination angle increases up to 30° (Tomren 1979; Iyoho 1980). For angles greater than 30°, particles may settle on the low side of the annulus, significant changes may occur in cuttings-fluid-flow patterns, and cuttings dunes or beds may build up. The cuttings beds or dunes formed at inclination angles between 30 and 60° are not stable and may result in cuttings avalanches. Variations in cuttings-moving patterns and unstable beds or dunes make inclinations between 30 and 60° a very difficult region for cuttings transport in deviated wells.

Cuttings-transport problems are one of the major contributors of well downtime. Real-time (RT) hole-cleaning models (Cayeux et al. 2016) have reproduced experimental evidence (Tomren et al. 1986; Larsen et al. 1997) that the transport of cuttings depends on the local conditions along the borehole (hole geometry, inclination, fluid velocity, drillpipe-rotational speed) and that cuttings-particles transport is governed by two key mechanisms: advection of particles in suspension and rate of cuttings-bed erosion (i.e., the lifting of particles into suspension from an already-formed cuttings bed).

Adari et al. (2000) claim the most-critical parameters to be fluid-flow rate, density and rheological properties, wellbore geometry and inclination, drillpipe eccentricity, drillpipe-rotational speed, and cuttings density and morphology. A generic set of parameters has been formulated with the focus on oil drilling in general (Nazari et al. 2010). A dedicated case-parameter description with value ranges has been established for coiled tubing (CT) using previously published studies (Kelessidis and Bandelis 2004).

Types of Drilling Operations and Scenarios. Generalizing drilling operations and scenarios is very often not possible because hole-cleaning problems are case and field sensitive. Thus, various hole-cleaning practices exist for the specific drilling operations, such as conventional, directional, liner, high-pressure/high-temperature (HP/HT), extended-reach, deepwater, CT, and aerated drilling. For deepwater and liner drilling, the constraint of keeping equivalent circulating density (ECD) within the available pressure window makes it challenging to achieve a sufficient circulation rate for maintaining a clean hole. HP/HT wells, by definition, require a higher-density fluid, which typically requires high solids loading, imposing extra challenges on cuttings transport and ROP. For horizontal flows, hole

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cleaning may be more efficient if a low-viscosity fluid is pumped in turbulent flow rather than a high-viscosity fluid in laminar flow. For inclined or horizontal flows, pipe rotation may be required to achieve good hole cleaning. The major differences between conventional rotational drilling and CT drilling are the absence of pipe rotation and the continuous circulation of drilling fluids (Leising and Walton 2002). For a typical CT drilling job, the challenge is achieving the circulation rate required to keep the hole clean.

During operations, several challenges pertaining to hole cleaning are encountered while making connections, tripping in, tripping out, and drilling ahead. Existing operational guidelines include the following:

- During tripping-in and tripping-out operations, the hole should be circulated until shakers are clean. Should the drag increase gradually while running in hole or pulling out of hole, the string should be reciprocated with low rotation and circulate a minimum of 3 or 4 bottoms up to try to mechanically wipe out the cuttings beds[1].
- Before making connections while running in hole, circulate the hole at the planned-section flow rate to evacuate cuttings surrounding the bottomhole assembly. After making the connection, pump rates should be brought up in steps before continuing drilling[1].
- During drilling ahead, poor hole-cleaning symptoms are abnormally low cuttings discharge, large amount of fill after trips, high pick-up weights, poor drillstring-weight transfer, stuck pipe, high ECD, high torque and drag, reduced penetration rate, and difficulty in running casing and packing off (Mims and Krepp 2007). In vertical sections, cuttings transport is optimized by increasing mud viscosity, maintaining a high yield point (YP), high gel strength, high YP/plastic viscosity (PV) ratio, using viscous sweeps, and maintaining laminar flow (Mims and Krepp 2007). In horizontal sections, maintaining turbulent flows and low viscosities is considered beneficial for cuttings transport (Cayeux et al. 2014).

Circulating with the bottomhole assembly in the same spot can lead to washouts and out-of-gauge hole, which can be detrimental to completion and production. Time spent on cleaning operations also adds to cost. Being able to more accurately determine how much cleaning is sufficient for the individual well would therefore be beneficial. Better knowledge and modeling can help achieve this.

Types of Research Methods. Various research methods have been used in cuttings-transport research. Here, we distinguish between laboratory experiments (modeling the well on a laboratory scale with physical experiments) and virtual models (virtual experiments/simulations on computing hardware), such as RT/mechanistic models, or various types of physics-based, multidimensional models such as computational fluid dynamics (CFD).

A conceptual overview of the logical relationships of different types of research methods and the actual drilling process is provided in **Fig. 1.** RT models, as well as mechanistic and 1D models, predict wellbore[2] states (in RT). Vice versa, they can to a certain extent be validated with RT data for a particular wellbore. Thus, RT models have to be fed with input data, and they require a parameter set describing the relevant case parameters of the problem along with numerical values of these (configuration data).

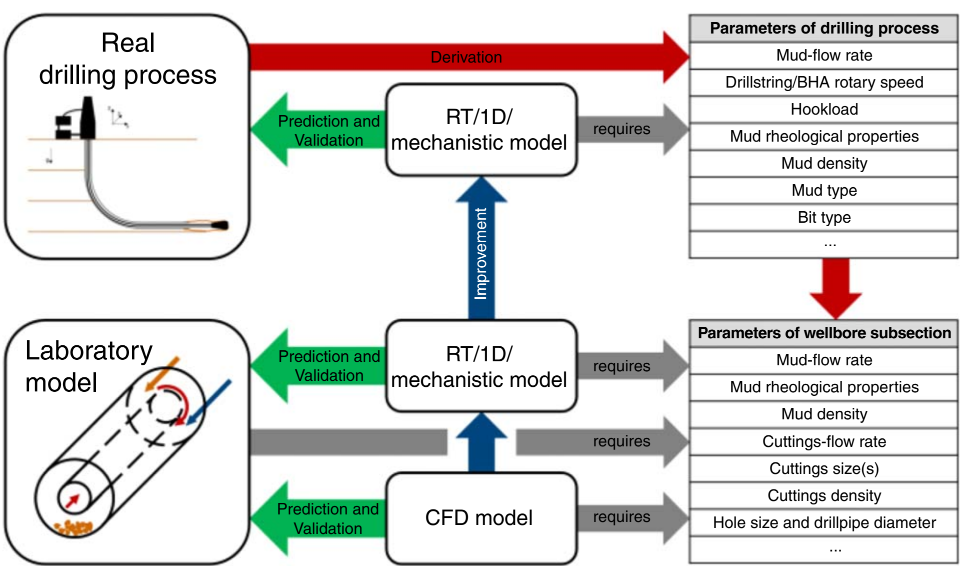

Fig. 1—Logical relationships of different types of research methods applied to cuttings-transport modeling. BHA = bottomhole assembly.

Cuttings-transport studies, on the other hand, usually investigate a small element of the wellbore, or a wellbore subsection[3]. A laboratory model uses an annular geometry with the length being approximately three orders of magnitude smaller than the wellbore. Through experiments on this level, one may directly study effects relevant for cuttings transport. Ideally, data from laboratory experiments are combined with 3D CFD modeling to gain a better understanding of the process. Using this understanding, improvements can be made to mechanistic models for RT applications.

Virtual models on the wellbore-subsection level again require a case-parameter set to provide a solution. This set of parameters has to equally serve as a specification for the laboratory model to validate the simulation with laboratory results.

The end goal is the correct interpretation of what is going on in different parts of the well in terms of cuttings transport using simulations and measurable data.

[1]Internal drilling guidelines, Neptune Energy Norge AS.

[2]"Wellbore" refers to the whole wellbore and takes a holistic view on the process.

[3]"Wellbore subsection" refers to an annular element downhole (with a length on the order of one drillpipe element or fewer) and is equivalent to the domain of interest in experimental or CFD cuttings studies.

Experimental/Laboratory. Laboratory experiments may be used for development of models for predicting the flow behavior in the annulus. To analyze the flow, measurements of flow conditions, such as temperature and pressure, are required. To enable the use of advanced-measurement/visualization techniques, one usually needs to use translucent drilling-fluid substitutes. High-time-resolution optical measurements are needed to capture transient phenomena, including visualization of flow patterns and measurement of velocity profiles. In addition, fast pressure transducers are needed to measure fluctuating pressure gradients in the annulus.

RT/1D/Mechanistic. The main purpose of RT drilling-process models is to support decision making on the rig as well as enable automation of drilling (Florence and Iversen 2010). Thus, these models need to deliver solutions in RT with a certain accuracy. Several flow patterns may occur in annular wellbore flows depending on the operational conditions. This makes it difficult to identify one mechanistic model that can cover all relevant flow patterns. Hence, various mechanistic models are used with respect to different flow patterns. However, in contrast to CFD models, RT models are usually 1D with respect to multiphase-flow and cuttings-transport calculations. In recent years, computational intelligence such as artificial neural networks has been used to build better cuttings-transport models, either with CFD data (Rooki et al. 2014) or with experimental data (Ulker and Sorgun 2016).

***CFD [Direct Numerical Simulation (DNS) and Reynolds-Averaged Navier-Stokes (RANS)]* Modeling.** CFD can be used to investigate a 3D fluid problem to obtain a 3D solution, providing pressure and velocity fields. If a second phase, such as dispersed particles/cuttings, is part of the problem, this can be treated either as a second continuum (Eulerian-Eulerian concept) or as individual particles (Eulerian-Lagrangian method). In the latter case, more computational effort is required because the particle trajectories are computed for each particle.

Mainly depending on the available computational power and the desired accuracy of the result, the following concepts can be distinguished:

- DNS resolves turbulence on all length and time scales down to the Kolmogorov (1962) length and time scale, which is the smallest relevant length and time scale in turbulent flows where energy dissipation takes place.
- Large eddy simulations resolve turbulence on length and time scales larger than grid size and timestep, thus resolving large eddies, but not model turbulence on subgrid scales.
- RANS approaches model the effect of turbulence on all length and time scales. The respective turbulence model is chosen considering the physics of the problem.

The RANS method is in general used for CFD cuttings-transport-modeling purposes because less computational power is required. For an overview of CFD work, the reader is referred to recent review papers (Kelin et al. 2013; Xiaofeng et al. 2013a; Li and Luft 2014b). Concerning this study, the relevant point to note is that the number of modeling parameters increases with the amount of modeling applied to describe the relevant physics (e.g., turbulence and/or particle forces).

Problem Description and Scope of This Paper. Comparison between different hole-cleaning-study results is challenging because characteristic parameters vary for different studies. To study the various mechanisms and processes influencing hole cleaning, studies are usually performed on simplified cases, as a result of limiting the set of case parameters that define the problem. It seems that there is no common set of case parameters applied in the drilling industry for hole-cleaning research. It is therefore difficult to compare existing experimental and simulation studies **(Table 1)** to quantify the effect of individual parameters. Subsequently, mainly qualitative statements are made in review papers (Table 1).

Studies		References
Experimental/laboratory		Bizhani et al. (2016); Piroozian et al. (2012); Nguyen et al. (2010); Duan et al. (2008); Ramadan and Miska (2008); Chen et al. (2007); Garcia-Hernandez et al. (2007); Ozbayoglu et al. (2007); Duan (2006); Hosokawa and Tomiyama (2004); Capo et al. (2004); Miska et al. (2004); Li and Walker (2001); Ramadan (2001); Sanchez et al. (1999); Doron and Barnea (1996); Larsen (1990); Bizanti and Blick (1983); Sifferman et al. (1974)
Analytical/numerical/ RT/mechanistic/1D	Conventional	Naganawa et al. (2017); Xie et al. (2015); Zhang (2015); Sorgun (2013); Wang et al. (2011); Olasunkanmi (2011); Hemphill and Ravi (2010); Guo et al. (2010); Salazar-Mendoza and Espinosa-Paredes (2009); Duan et al. (2009); Petersen et al. (2008); Costa et al. (2008); Garcia-Hernandez et al. (2007); Espinosa-Paredes et al. (2007); Naganawa and Nomura (2006); Ramadan et al. (2001, 2003, 2005); Li et al. (2004); Cho (2001); Masuda et al. (2000); Kamp and Rivero (1999); Nguyen and Rahman (1998); Santana et al. (1998); Hemphill (1997); Larsen et al. (1997); Kenny et al. (1996); Ford et al. (1996); Campos et al. (1994); Rasi (1994); Clark and Bickham (1994); Iyoho and Takahashi (1993); Martins and Santana (1992); Gavignet and Sobey (1989)
	CT	Cho et al. (2000, 2002, 2013); Li and Aitken (2013); Kelessidis and Bandelis (2004); Takahashi (2003); Leising and Walton (1998, 2002); Walker and Li (2000)
	Foam	Rooki et al. (2014); Duan et al. (2010); Cheng and Wang (2008); Osunde and Kuru (2006); Ozbayoglu et al. (2002)
	Aerated	Adeboye and Akinribide (2013); Naganawa et al. (2002)
CFD		Akhshik et al. (2015); Zhang (2015); Dykes (2014); Xiaofeng et al. (2013b, 2014); Yilmaz (2012); Hamne (2014); Ofei et al. (2014); Ofei and Pao (2014); Osgouei et al. (2013); Hajidavalloo et al. (2013); Rooki et al. (2013a, b); Schwalbert et al. (2013); Mme and Skalle (2012); Han et al. (2010); Al-Kayiem et al. (2010); Sorgun (2010); Pereira et al. (2010); Wang et al. (2009)
Reviews		Manjula et al. (2017); Ofei et al. (2015); Li and Luft (2014a, b); Shah et al. (2014); Kelin et al. (2013); Xiaofeng et al. (2013a); Kamyab et al. (2012); Nazari et al. (2010); Pilehvari et al. (1999)

Table 1—Types of research methods, with respective references.

The aim of this paper is to suggest a methodology for deriving a well-defined and standardized set of geometrical, operational, and environmental case parameters describing selected drilling operations and procedures as well as simplified problems. Applying such a methodology before cuttings-transport studies may increase alignment in research within the field of cuttings transport, similar to definitions available in other industries such as a standard wind-turbine model in wind-power research (Jonkman et al. 2009) or the Sod (1978) shock tube in CFD modeling. In addition, such a methodology may enable better definitions and benchmark specifications of industry-relevant case parameters. A simple methodology is presented providing benchmarks/case-parameter sets for both the entire wellbore and for a wellbore subsection. Standard parameters related to cuttings transport are suggested as an example and discussed with regard to their application in modeling, both experimentally and through simulation. Concerning the particular influences of parameters on cuttings transport, the reader is referred to review papers as summarized in Table 1 (Ofei et al. 2015). Please note that the actual process of cuttings-transport modeling is not the scope of this paper. Instead, the paper addresses the specification method of relevant parameters required to model cuttings transport.

Structure of This Work. In the next section, we present the methodology we have applied to derive industry-relevant case parameters. Here, we distinguish between the major research methods in use to model two different spatial scales: simplified mechanistic models typically used to model the entire wellbore, and laboratory experiments, as well as CFD, typically used to model an annular element with a specific length, such as a wellbore subsection.

In the Results section, we apply the introduced methodology to the particular example of an 8.5-in. wellbore section[4] that is representative of the Norwegian Continental Shelf (NCS). All relevant case parameters are identified and their validity ranges/numerical values are compared with those of recent cuttings-transport studies. A discussion of the methodology and the comparison are provided in the next section, followed by a conclusion in the final section.

Methodology

Developing parameter sets for different drilling operations and procedures conceptually follows the red arrows indicated in Fig. 1. An overview of this methodology is provided in this section and illustrated with a particular example. Additional parameters relevant for virtual modeling, such as CFD and experimental modeling, are briefly presented.

Derivation of Case-Parameter Sets for Cuttings-Transport Problems. Parameter sets for cuttings-transport studies are derived from a specific drilling operation and drilling procedure. A particular set of such parameters defines a particular problem or case. **Fig. 2** depicts a conceptual overview of the proposed methodology. Once a drilling operation and procedure is defined, one can in general identify the relevant parameters determining the problem and also the characteristic ranges for these parameters. The first level of Fig. 2 addresses the wellbore as a whole, while the second level focusses on a particular wellbore subsection. Again, a list of parameters together with numerical values is required to describe the problem on this level. When investigating a particular problem, one usually studies specific operating points of the system of interest. Each working point is represented by a list of case parameters, with only one numerical value per parameter (or a time series if the problem is transient); the sum of all working-point-parameter lists is usually termed the test matrix.

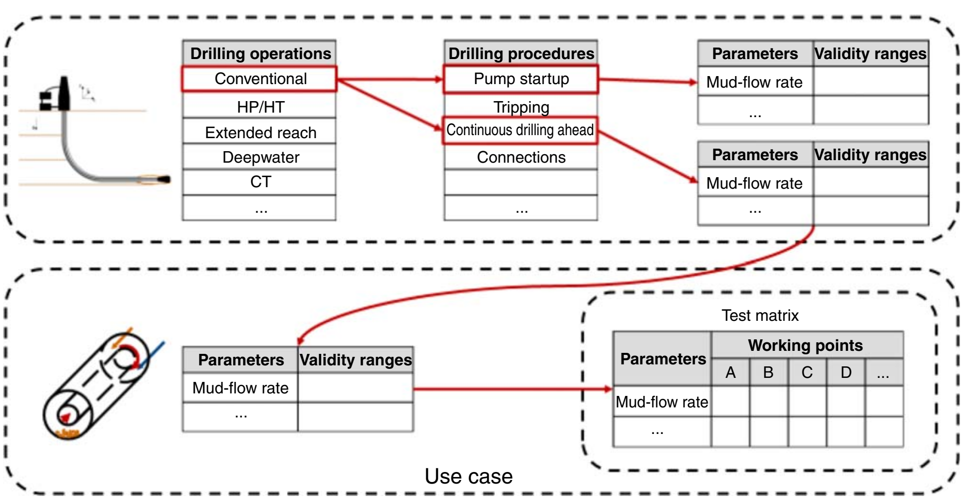

Fig. 2—Conceptual overview of parameter-set derivation for cuttings-transport problems. (Top) Drilling process/wellbore scale; (bottom) wellbore-subsection scale.

We consider the complete description of a particular problem, as depicted in Fig. 2, a use case[5] for cuttings-transport studies by either experimental or virtual modeling.

Parameter Space for Cuttings-Transport Problems. The parameter space of a cuttings-transport problem can be visualized as depicted in **Fig. 3.** The main dimensions shown are sections generally correlating with true vertical depth (TVD) and/or measured depth (MD) and sections currently drilled in, generally as time-series, as well as all other relevant parameters. The red space in Fig. 3 encompasses the full wellbore at all times, and consequently all sections and depths drilled in. By defining a specific section of interest (e.g.,

[4]In Norway, a mixture of SI and oilfield units is typically used. We use the SI system with wellbore sections expressed in inch lengths.

[5]In software and systems engineering, a “use case” is a description of interactions between an actor and a system to achieve a goal. A use case, in our context, is the full description of a physical system/process that is to be modeled.

the 8.5-in. section as the section currently drilled in), one can refine the parameter space. However, the spatial focus is still the wellbore. To yield a parameter space relevant for cuttings-transport studies conducted in a laboratory or using CFD, a redefinition of this parameter space is required in such a way that it instead describes a particular wellbore subsection. It should here be noted that we can only define our parameter ranges as current characteristic ranges. Drilling methodologies and materials, including drilling fluids, are under continuous development. For example, there has been a historic development from simple vertical wells to deviated wells to extended-reach wells going continuously longer and deeper with increasing temperatures and pressures. Such development continuously extends the parameter ranges describing the drilling process.

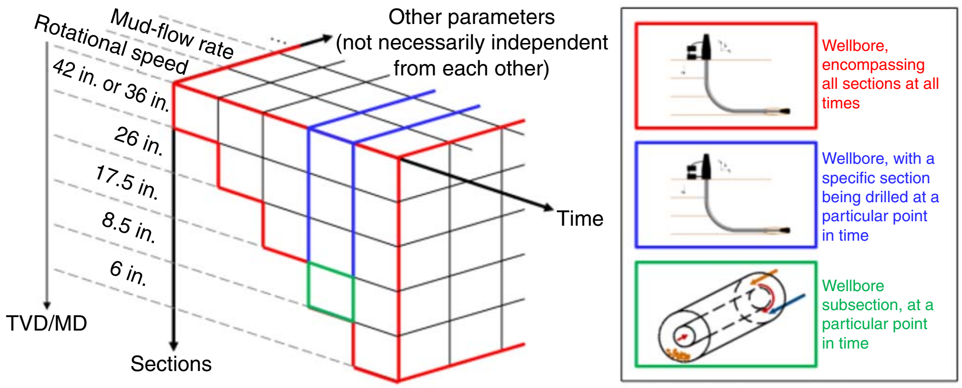

Fig. 3—Generic parameter space for cuttings-transport problems.

Wellbore. In drilling operations, cuttings transport needs to be considered over the duration of the drilling process. However, models applied in managing the process need to have the capability of modeling the dynamics of the drilling process on a shorter time scale, covering all the phases of the drilling process. We will here focus on two phases during conventional drilling: a quasisteady-state drilling ahead and a transient pump-startup phase. For the first phase, a parameter space of a generic cuttings-transport problem has already been presented (Nazari et al. 2010) using an abstract system/process view on drilling and cuttings transport. Parameters and variables are classified as inputs, internal states, or outputs.

We propose to elaborate on this concept as follows and as presented in **Fig. 4:**

- Mud rheological properties are to be expressed by constitutive equations with coefficients or tabulated data. We here use a simple Bingham model because it allows us to easily exploit aggregated well data available from the NPD. Surface rheological properties (e.g., YP and PV measured with a Fann viscometer on the drilling platform at room temperature and ambient pressure) are the input. True effective mud rheological properties (i.e., in-situ rheological properties of the mud downhole) mainly as a function of local or downhole pressure and downhole temperature (Maglione et al. 2000) are internal states.
- All hole angles and hole sizes for different wellbore sections are to be specified. Ideally, this information is related to a given trajectory.
- Lithology needs to be expressed by various parameters relevant to cuttings transport—at least rock type, density, porosity, and bottomhole temperature or temperature gradients, if available.
- Cutting size is to be specified in more detail, ideally by a cuttings-size distribution.
- Eccentricity is to be described by two normalized spatial coordinates (Cartesian coordinate system e_x and e_y or cylindrical coordinate system e_R and e_θ) instead of one because it describes the position of the drillstring in a 2D space (Menand et al. 2006). Ideally, this information is related to a given trajectory.
- Hookload is not considered to be an input parameter, in contrast to the view of Nazari et al. (2010). We rather think of it as an internal state because block position and/or the speed of the drillstring are the input variables manipulated on the rig. Furthermore, we cannot relate it to a specific parameter used in experimental or virtual cuttings-transport modeling on the wellbore-subsection level.
- Bottomhole pressure (BHP) is considered to be an output parameter because it is a consequence of various other parameters such as mud-flow rate, mud density, and mud rheological properties, as well as TVD. Together with ECD, it can be indicative of the quality of hole cleaning during operations.
- Temperature is a spatial boundary condition that typically increases with depth and will mainly affect the in-situ mud rheological properties.

Exact parameters of lithology[6], cuttings size, and eccentricity are unknown in actual drilling operations, and projections and estimates are typically made for modeling.

The relevance of individual parameters for hole cleaning varies, as indicated in Fig. 4. These input parameters may be correlated. For example, selection of mud type and rheological properties both depend on the formation drilled.

The scope of this approach is to handle the complete wellbore. However, the parameters do not directly apply to any specific wellbore subsection. Clearly, specified local parameters are needed to investigate cuttings transport for experimental and virtual models.

Wellbore Subsection. When applying the elaborate concept depicted in Fig. 4 to a certain wellbore subsection to model cuttings transport in 3D (corresponds to the second level of Figs. 1 and 2 as well as the particular wellbore subsection in Fig. 3), one needs to redefine the input vector of parameters as illustrated in **Fig. 5.** What is an internal state of the previous problem formulation becomes an input and has to be specified (i.e., eccentricity, cuttings sizes, and effective apparent rheological properties). Some of the outputs of the previous level (e.g., ROP and BHP) consecutively become an input parameter. Additional parameters appear, such as the cuttings-flow rate. The length of the domain of interest has to be specified as well. New internal states arise, such as 3D velocity and pressure fields, cuttings-bed height, and turbulent kinetic energy.

[6]For development operations, there may be some knowledge of lithology from neighboring wells; for exploration wells, less so.

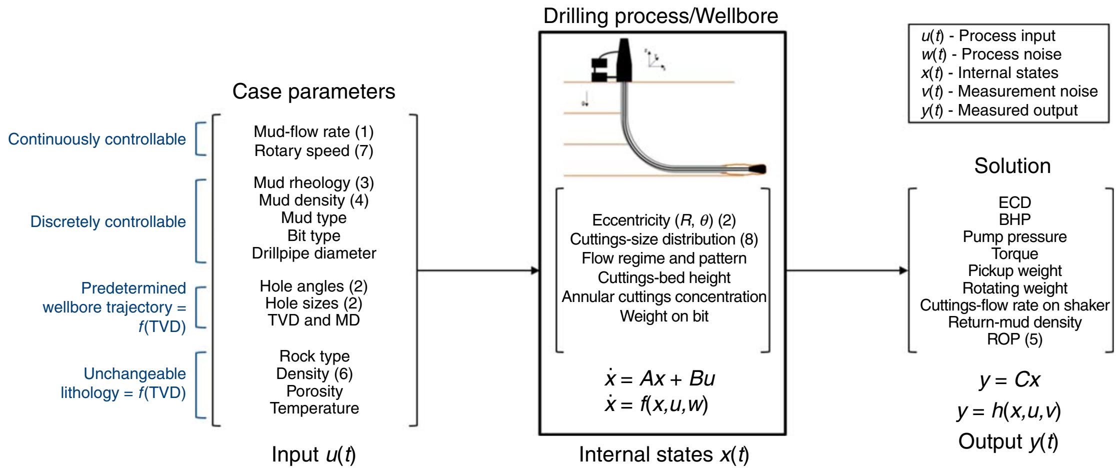

Fig. 4—Elaborated process view of Nazari et al. (2010) for the drilling process. The numbers 1 through 8 rank the parameters' qualitative effect on cuttings transport using Adari et al. (2000). The parameters A, B, and C are matrices describing the properties of the system to be controlled.

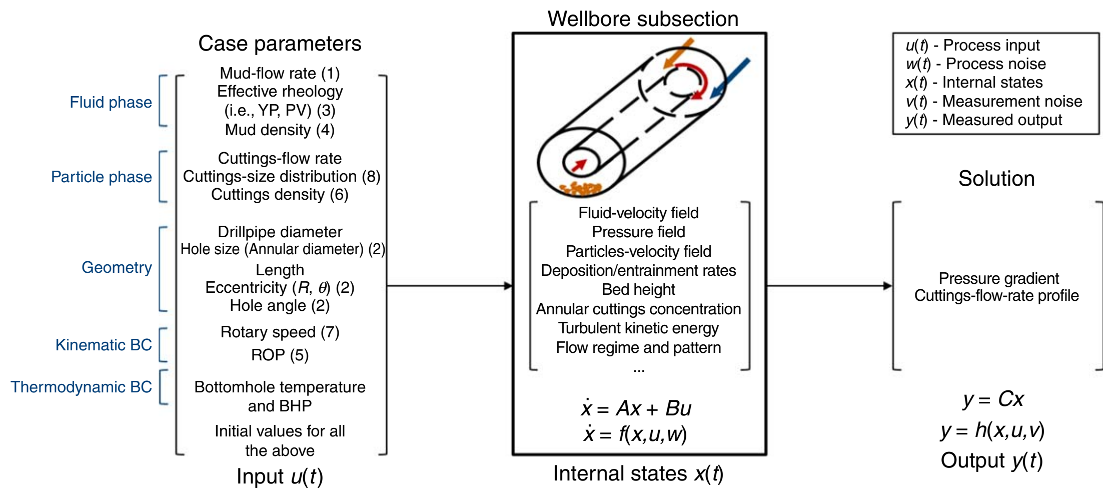

Fig. 5—Elaborated process view of Nazari et al. (2010) for a wellbore increment downhole. See Fig. 4 for explanation of the numbers 1 through 8 and the parameters A, B, and C. BC = boundary condition.

After having established parametric ranges for the scope of the wellbore, one needs to derive values for the inputs stated in Fig. 5 to describe a particular wellbore subsection. Because they are unknown, well-informed estimates are made from field data (Mims and Krepp 2007; Murchison 2001) or, if available, results from a RT/1D/mechanistic model of the previous problem formulation may be exploited.

Research-Method-Specific Parameters. In addition to the relevant case parameters presented so far, further parameters have to be considered and specified depending on the applied method of research. We briefly present the most-relevant ones in this section. However, the influences of the parameters specific to the individual research methods are beyond the scope of this paper.

Laboratory Experiments. Experiments on well hydraulics and cuttings transport should aim to simulate the drilling conditions as closely as possible. The annular and pipe geometry, fluid, and particle properties as well as dynamics of the experiments should be defined using the best choice of scaling laws and well-flow parameters mentioned in Fig. 4 (for the wellbore) and Fig. 5 (for the wellbore subsection). However, scaling experiments with non-Newtonian fluids is challenging. Because of the nonlinear-flow characteristics of these fluids, exact scaling of such problems is in general not possible. Furthermore, many dimensionless parameters may oppose each other while attempting to downscale the model. Because of limitations on the possible parameter values, these might even come in mutual conflict when attempting downscaling. Therefore, a selection of dimensionless parameters is required, depending on our best physical understanding. The use of scaling methods will help to achieve a scenario that is as close as possible to real-well conditions. Provided that we are able to understand and model such scaled processes, the same models should also be adaptable to actual-drilling conditions.

With this information, measurement devices such as flow meters, differential-pressure cells, thermometers, and densitometers as well as components such as pumps, separators, and heat exchangers may be selected to control the flow conditions and fluid rheological properties in the flow loop. The pipes can be transparent for low-pressure flow loops, allowing for visual observation. Nonintrusive measurement techniques may then be used, such as laser Doppler anemometry, particle-image velocimetry, and ultrasonic-velocity profiling, to measure the instantaneous velocity field. Ultrasonic-velocity-profiling techniques have the advantage of being applicable for both low and high pressures and even nontransparent pipes and fluids, provided adapters for good acoustic transmission are used.

Depending on the particular experimental setup, additional parameters arise, such as type, position, accuracy, and calibration of measurement devices and components.

RT/1D/Mechanistic. The RT or 1D flow models will have parameter sets very similar to the CFD models. In general, 1D models are mechanistic but rely heavily on simplified closure models that can be tuned to experiments or to operational data. Such closure models enable solving of the problems but may in some cases violate basic principles such as mass or energy conservation. Typical additional parameters required for 1D modeling but not for CFD are those relevant to system behavior: correct prediction of pressure waves, prediction of avalanches of cuttings, methods to handle complex rheological properties, and the applied methods for laminar, transitional and turbulent flows. We note that in the case of commercial simulators, some of the methods applied may be trade secrets and not specified. This is a parameter by itself that, for a third party, acts as an additional degree of freedom.

CFD. In general, additional parameters induced by CFD models vary with the particular approach applied. As an example, turbulence may be modeled by DNS, large eddy simulations, or RANS. For RANS, one has to select a particular turbulence model suited to the problem and specify the respective model parameters. Furthermore, the use of wall functions for modeling of flow in the boundary layer will add more parameters. Discretizing the domain with a computational mesh will result in parameters such as cell type, number of cells, and boundary-layer refinement. Depending on the flow pattern (among other parameters, such as available computational power), a multiphase-modeling approach (Eulerian-Eulerian vs. Eulerian-Lagrangian) has to be chosen. Within this selection, a particular model (i.e., two fluid or drift-flux for Eulerian-Eulerian and discrete-element method or dispersed-phase model/discrete-particle method for Eulerian-Lagrangian) with associated parameters is to be used. The description of forces acting on a solid particle, either through fluid/solid or solid/solid interaction, will introduce more model parameters. Boundary conditions add further parameters, as do the numerical schemes and procedures needed to solve the system of equations.

Results

Following the proposed methodology described previously, an example of parameter specification is provided for the selected case of a drilling-ahead scenario in conventional drilling. Two parameter sets are generated: one for the wellbore and one for a wellbore subsection. The latter is further compared with parameter sets of recent cuttings-transport studies. The section concludes with examples of relevant use cases for modeling purposes.

Example of Case-Parameter Sets. To provide a numerical example for the formulated methodology, we focus on a drilling-ahead procedure in a conventional-drilling operation, apply a regional focus on the NCS, and limit ourselves to water-based muds (WBMs) because these are the most relevant type of fluid systems in Norway[7]. For the wellbore scope, the 8.5-in. section is defined as the section drilled according to Fig. 3. For the wellbore-subsection scope, we focus on the 8.5-in. section specifically.

Wellbore. By exploiting publicly available exploration and appraisal wellbore statistics for the NCS (NPD 2015) and correlating data with MD, the following information is obtained, as summarized in **Table 2:**

- A general MD_{MSL} (MD, mean sea level) range of 1500 to 4500 m is estimated for wells incorporating an 8.5-in. section. As shown in the distribution analysis **(Fig. 6)** of the NPD wellbore data, this range accounts for 94% of all wells.
- Bottomhole-temperature range is estimated to be 50 to 150°C with regard to the specified conventional-drilling operation and exclusion of HT operations according to **Fig. 7.** The available data do not include information on thermal gradients.
- The PV range is estimated to be 10 to 60 mPa·s. A distribution analysis of the previously defined depth range **(Fig. 8)** shows that this range encompasses 95% of the distribution.
- The YP range is estimated to be 0 to 20 Pa. A distribution analysis of the previously defined depth range **(Fig. 9)** shows that this interval encompasses 95% of the distribution, and that for the considered depth range, more-non-Newtonian-like fluids with a YP $\neq$ 0 are used (55% vs. 64%).
- Mud density is estimated to be 1000 to 1800 kg/m^3 (corresponding to 1.0 to 1.8 g/cm^3). A distribution analysis of the previously defined depth range **(Fig. 10)** shows that this interval encompasses 96% of the distribution.

Parameter	Characteristic Range	Rationale
Mud-flow rate	1325–1515…1700–2300 L/min	Guidelines (Mims and Krepp 2007)
Rotational speed	0…60…70–100 rev/min	Guidelines (Mims and Krepp 2007)
Mud YP	0–20 Pa	Data analysis (NPD 2015)
Mud PV	10–60 mPa·s	Data analysis (NPD 2015)
Mud density	1000–1800 kg/m^3	Data analysis (NPD 2015)
Mud type	WBM	Project scope
Bit type	Polycrystalline diamond compact	Typically used on the NCS
Drillpipe diameter	4–5.5 in.	Typically used on the NCS
Hole angles	0–90°	Including appraisal wells
Hole sizes	36–6 in.	Data analysis (NPD 2015)
MD_{MSL}	1500–4500 m	Data analysis (NPD 2015)
Rock type	Sandstone, limestone, clay	Typical formations on the NCS
Density	Sandstone: 2000–2800 kg/m^3; lime: 1400–2900 kg/m^3; clay: 1800–2300 kg/m^3	Literature values (Fjaer 2008; Schön 1996); for sandstone, limestone, and clay
Porosity	Sandstone: 0.04–0.30; lime: 0.04–0.30; clay: 0.25–0.40	Literature values (Fjaer 2008; Schön 1996); for sandstone, limestone, and clay
Bottomhole temperature	50–150°C	Data analysis (NPD 2015)

Table 2—Wellbore-characteristic-parameter ranges for drilling-ahead procedure in a conventional drilling operation with focus on the NCS and the 8.5-in. section being the section currently drilled in.

[7]From the Neptune Energy Norge AS/Statoil ASA in-house source.

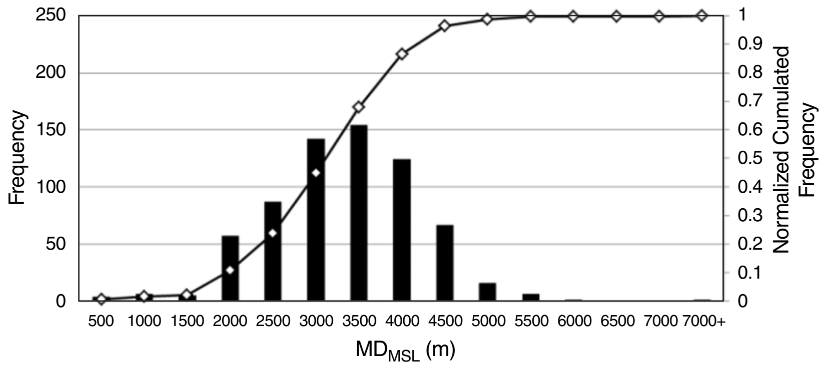

Fig. 6—MD_{MSL} distribution of 8.5-in. section of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM (NPD 2015).

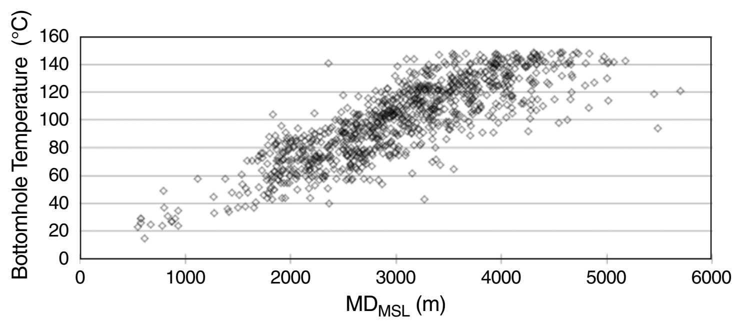

Fig. 7—Bottomhole temperature vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM (NPD 2015).

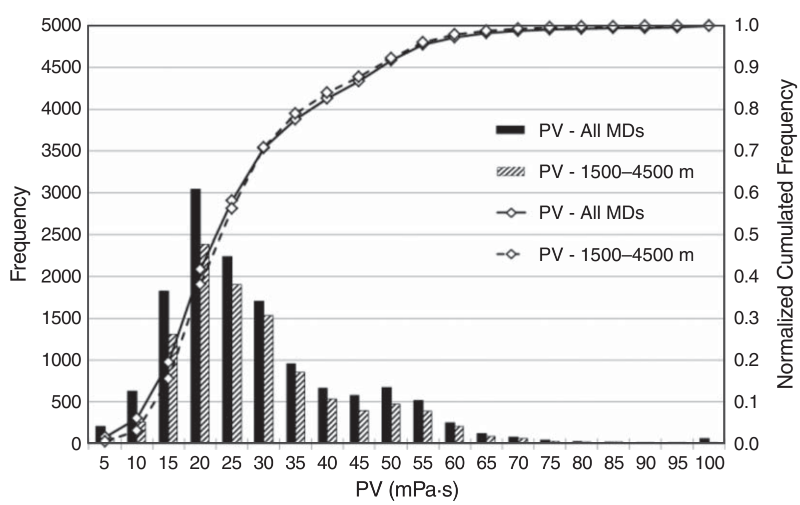

Fig. 8—PV distribution of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM, PV = 0 discarded (NPD 2015).

Because no further data are available to exploit, we make the following educated guesses for the remaining parameters:

- The desirable mud-flow rate range for effective hole cleaning is specified as 1700 to 2300 L/min, and the range of 1325 to 1515 L/min is considered the minimum for effective hole cleaning (Mims and Krepp 2007)[8].
- The desirable rotational-speed range of the drillpipe for effective hole cleaning is 70 to 100 rev/min, and 60 rev/min is considered the minimum rotational speed for effective hole cleaning (Mims and Krepp 2007).
- Drillpipe sizes typically used on the NCS to drill 8.5-in. sections are 5 and 5.5 in.
- In recent times, typically polycrystalline-diamond-compact bit types have been used on most runs while drilling the 8.5-in. sections on the NCS[9].

[8]In case of a transient-pump-startup scenario, a profile is to be specified. Typically, one would start at 0 L/min and ramp up to a specified flow rate in a certain period of time, with two stops during the ramp. The first stop is performed to check for return flow and the second is to check for activation of MWD.

[9]From the Neptune Energy Norge AS in-house source, using bit-vendor statistical information of bits used during 2015 and 2016 in the 8.5-in. sections on the NCS.

- Hole angles range from 0 to 90° because all inclinations can generally occur in a well. However, depending on the particular well profile/trajectory, not all sections will feature all inclinations. For instance, the 42/32 in. and the 26/24 in. are typically drilled vertically on most wells in the NCS.
- Rock types are specified as limestone, sandstone, and clay because these are the main formations on the NCS. Caused by lack of data, we use textbook values (Schön 1996; Fjaer 2008) to estimate the characteristic ranges of the rocks' density and porosity, as indicated in Table 2.

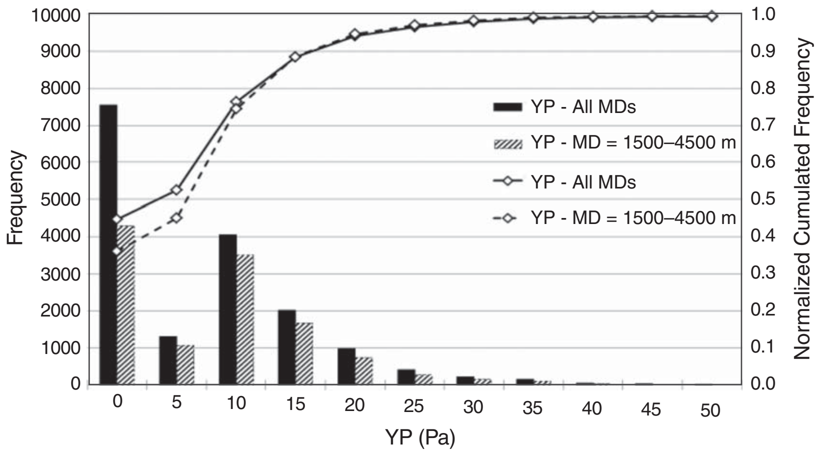

Fig. 9—YP distribution of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM (NPD 2015).

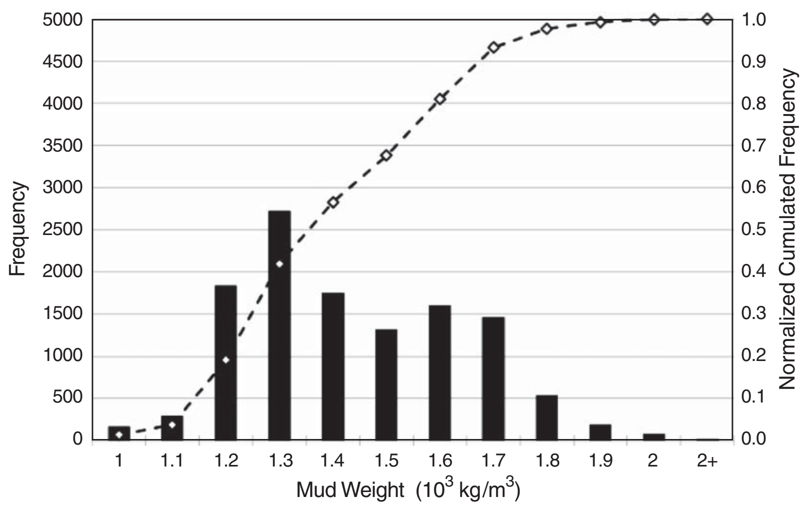

Fig. 10—Mud-weight distribution of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM, MD_{MSL} = 1500–4500 m (NPD 2015).

Wellbore Subsection. We choose to primarily work with the 8.5-in. section for specifying meaningful parameter-value ranges for a wellbore subsection. Value ranges are specified using the rules of thumb as follows and as summarized in **Table 3:**

- ROP is estimated to range from 5 to 30 m/h for normal operating conditions. There exist concepts such as an empirical equation for drillability (Mitchell and Miska 2011) or ROP models (Warren 1987). However, we use the experience from drilling operations because at this point we are primarily concerned with a typical range.
- Cuttings-flow rate may be estimated using mass conservation (Bourgoyne et al. 1991) as

$$\dot{V}_{\mathrm{Cut}} = \frac{1}{93}\frac{\pi(1-\phi)d^2}{4}ROP, \quad (1)$$

where ϕ is rock porosity, d is bit/hole diameter (in.), ROP is measured in m/h, and 1/93 is a conversion factor to yield the cuttings flow rate (L/min). Assuming ROP and porosity ranges as indicated in Table 3, the range of potential cuttings-flow rates is estimated to be 5 to 18 L/min for the 8.5-in. section.

- Eccentricity of the drillpipe ranges from zero to unity in the radial and 0 to 360° in the circumferential direction. In general, all eccentricities may occur because of well trajectory and deformation of the drillstring (Menand et al. 2006).
- Effective mud rheological properties are known to be a complex function of well temperature, pressure, and shear rate as well as mud formulation and structure (Maglione et al. 2000). Mud rheological properties will be largely affected by the mud temperature downhole, which depends on heat transfer to the mud and is not directly measurable. In most cases the drilling mud becomes less viscous the deeper and warmer it gets (White et al. 1997; Maglione et al. 2000; Santoyo et al. 2001). WBM systems based on bentonite and potassium chloride used on the NCS also appear to show this behavior (Torsvik et al. 2014). However, we choose not to

apply any changes to the values describing the wellbore scope as indicated in Table 2 when transferring to the wellbore-subsection scope as indicated by Table 3 because changes in effective viscosity apparently occur in the same order of magnitude. Furthermore, there apparently are examples where the effective viscosity may increase with depth and temperature (Santoyo et al. 2001).

- The length of the subsection of interest equals the length of the annular geometry used for modeling purposes. We consider it to be an open parameter because it depends on the length scales of the phenomena to be modeled (e.g., dune movement vs. velocity profile). On the other hand, it is restricted by available computational power and/or laboratory space.
- Cuttings size is a major unknown. It is dependent on formation type, area drilled, and bit type, among other factors. Cuttings size and irregularity will also typically be reduced from one wellbore subsection to another because the cuttings are subjected to the mechanical forces of the drillstring and shearing/collision with each other. Accessibility of cuttings-size data is limited. For this reason, we are only able to state a generic interval of 0.007 to 40 mm for shale formations derived from previous studies (Saasen et al. 2013; Rye 2005)[10].
- Downhole pressure is an input on the wellbore-subsection level and it is known to affect mud rheological properties to some extent. However, the change of effective viscosity occurs in the same order of magnitude and highly depends on the particular drilling-fluid system used. Furthermore, in CFD modeling, one would typically only deal with the pressure difference over the length of the computational domain and not with the absolute pressure. Hence, BHP is mentioned as an input on the wellbore section, but not quantified.
- In principle, temperature is also an input on the wellbore-subsection level. However, an isothermal approach is typically used for CFD cuttings-transport modeling, with the exception of Schwalbert et al. (2013). This is also the case in experimental cuttings-transport studies, where experiments are typically conducted at laboratory temperature and do not replicate the temperature gradients and respective heat transfers of real-wellbore flows. Temperature significantly changes the rheological properties, as briefly outlined previously.

All other parameter ranges remain the same because of the lack of more-detailed information.

Parameter	Characteristic Range	Rationale
Mud type	WBM	Project scope
Mud-flow rate	1325–1515…1700–2300 L/min	Guidelines (Mims and Krepp 2007)
Mud YP	0–20 Pa	Data analysis (NPD 2015)
Mud PV	10–60 mPa·s	Data analysis (NPD 2015)
Mud density	1000–1800 kg/m^3	Data analysis (NPD 2015)
Cuttings-flow rate	5–18 L/min	Using Eq. 1
Cuttings size	0.007–40 mm	Literature values (Rye 2005; Aquateam 2014; Saasen et al. 2013)
Cuttings density	2000…2800 kg/m^3	Literature values (Schön 1996; Fjaer 2008) for sandstone
Porosity	0.04–0.30	Literature values (Schön 1996; Fjaer 2008) for sandstone
Drillpipe diameter	5.5–4.5 in.	Typical values on the NCS
Hole size	8.5 in.	Covers 0…90° hole angles, turbulence
Length of element	Open parameter	= *f* (phenomena, computational power, laboratory space)
Hole angles	0–90°	Exploration and appraisal wells
Eccentricity (e, θ)	0–1, 0–360°	Buckling of pipe in all spatial directions
Rotational speed	0…60…70–100 rev/min	Guidelines (Mims and Krepp 2007), rotational bottomhole assembly
ROP	0…5–30 m/h	Typical values on the NCS
MD_{MSL}	1500–4500 m	Data analysis (NPD 2015)
Bottomhole temperature	50–150°C	Data analysis (NPD 2015)

Table 3—Wellbore-subsection-characteristic-parameter ranges for drilling-ahead procedure in a conventional drilling operation with focus on the NCS and the 8.5-in. section being the section of interest.

Comparison With Recent Cuttings-Transport Studies. A comparison of the established parameter sets with those of some arbitrarily selected recent cuttings-transport studies is provided in this subsection.

Table 4 shows the parameter sets of three CFD cuttings-transport studies (Al-Kayiem et al. 2010; Dykes 2014; Akhshik et al. 2015) with the corresponding experimental studies used for model validation (Tomren et al. 1986; Sanchez et al. 1999; Osgouei 2010) as well as the parameter sets of one experimental study (Taghipour et al. 2013).

Applied parameter values are seldom comprehensively communicated. For instance, in one case, a cuttings-flow rate is not provided (Akhshik et al. 2015)[11], whereas in another case, neither ROP nor cuttings-flow rate are provided (Akhshik et al. 2015)[12]. In addition, a direct comparison of different studies is often not straightforward because different rheology models are used[13].

[10]A particle-size distribution of cuttings of an exploration well in the Barents Sea (no formation/section provided) indicates a range of 0.007 to 7 mm (see Saga 1994 in Rye 2005). A more-recent study (Saasen et al. 2013) established the particle-size distribution of tophole NCS drill cuttings using data for two different wells (36-, 26-, 17.5-, and 12.25-in. sections). For a 36-in. section in sand, formation cuttings between 0.02 and 2 mm were found. For 26-, 17.5-, and 12.25-in. sections in shale, formation cuttings between 0.02 and 20 mm were found, with a trend toward finer grains for deeper sections. Up to 40 mm cuttings were observed visually.

[11]The value provided in Table 4 has been calculated using Eq. 1 assuming a porosity of zero.

[12]The value provided in Table 4 has been obtained using the corresponding experimental paper.

[13]We have obtained PV and YP from power-law- (Tomren et al. 1986; Al-Kayiem et al. 2010; Taghipour et al. 2013) or Herschel-Bulkey-model (Akhshik et al. 2015) coefficients using definitions (*API RP 13D* 2010).

Virtual Modeling	This Paper	Dykes (2014)	Dykes (2014)	Al-Kayiem et al. (2010)	None	Akhshik et al. (2015)	Akhshik et al. (2015)
Experimental modeling	–	Tomren et al. (1986)	Sanchez et al. (1999)	None	Taghipour et al. (2013)	Tomren et al. (1986)	Osgouei (2010)
Mud type	WBM	Freshwater with no additives	Bentonite or polymer solution	Bentonite + xanthan gum	WBM with xanthan gum and laponite	Carbopol/ high-viscosity bentonite	Water
Mud-flow rate (L/min)	0…1325–1515…1700–2300	473–852	757–1892	2271–3407	193–492	377–757	94–234
YP (Pa)	0–20	–	7	42–55	3	7	–
PV (mPa·s)	10–60	1	7	9.5–15.7	4	18	1
Mud density (kg/m^3)	1000–1800	998	?	1013–1043	998	1013, 1018	998.00
Cuttings-flow rate (L/min)	5–18	3.4	5.8	2.6	1.0	3.5	1.3…2.6
Cuttings size (mm)	0.007–40	6.350	2.54, 6.350	2.54, 4.45, 7	0.9–1.6	6.350	2.000
Cuttings density (kg/m^3)	2000–2800	2651	2640	2570	2700	2619	2300
Porosity	?	?	?	?	?	?	?
Drillpipe diameter (in.)	5.0	1.90	4.50	5.0	1.97	1.90	1.85
Hole size (in.)	8.5	5.0	8.00	9.88	3.93	5.0	2.91
Length of increment (m)	Open parameter	12.192	7.620	0.910	12.000	12.000	7.000
Hole angle (degrees)	0–90	0, 10, 20 … 90	40°, 65°, 80°, 90°	15, 20, 25, 30	0…30	0, 20, 40, 60, 80	90
Eccentricity (e, θ) (dimensionless, degrees)	0–1, 0–360	–0.5, 0, 0.5	0–1 (orbital motion)	0.00	0…1	0.50	0.623
Rotational speed (rev/min)	0…60…70–100	0, 50, 100	0, 25…150, 175	0	0, 50, 150	50	0, 80, 100, 120
ROP (m/h)	0…5–30	15.2	10.7	?	8.0	0.0	18, 24, 30, 37
MD_{MSL} (m)	1500–4500	?	?	1710 (“total depth of the well”)	?	?	?
Bottomhole temperature (°C)	50–150	?	?	?	28	?	?

Table 4—Wellbore-subsection-parameter set developed in this study compared with parameter sets of recent cuttings-transport studies.

Use Cases. Finally, we present different use cases for cuttings-transport-modeling problems. All are dependent on the examples provided previously.

A selection of defined use cases with regard to different levels of (modeling) complexity is depicted in **Fig. 11.** To build more-sophisticated models aggregated from simpler ones, the presented use cases are designed to address the multifaceted problem of cuttings transport with increased complexity. Thus, some of the use cases do not directly correspond to a cuttings-transport problem in drilling, but rather serve as an intermediate step toward more-sophisticated models, such as “in pipe” and “plan mud.” We distinguish between “steady” and “unsteady” problems with regard to the operational drilling parameters (e.g., a mud-flow rate of 1500 L/min vs. a mud-flow-rate profile of 0 to 1500 L/min with a flow-rate-gradient increase of 10 L/min/s[14]). Presumably, rheology models used in virtual modeling may have to be more sophisticated for the unsteady problems because drilling muds are time-dependent fluids in general.

We also distinguish between complex geometries and kinematic boundary conditions, such as flow in an annulus with a rotating drillstring, and simple geometries such as plain mud flow in a drillpipe.

For steady problems, the simplest case is pure Non-Newtonian pipe flow of plain mud (single-phase flow, no cuttings), which corresponds to flow through the drillpipe in our defined wellbore subsection (Case 1). A more-complex case is an annular geometry. Again, two levels of complexity can be investigated: plain mud (Level 1) and mud with dispersed cuttings (Level 2), which correspond to a successfully flushed wellbore subsection and a flushing procedure, respectively. The third level of complexity is the drilling-ahead scenario, as described in Table 3. Again, we distinguish between with (Level 2) and without cuttings (Level 1) corresponding to continuous

[14]The terms “steady” and “unsteady” refer to the input parameters and not to the internal states and/or outputs. In case of turbulence and dispersed cuttings, the solution (internal states, outputs) will always be transient/unsteady.

drilling ahead and a flushing procedure, respectively. The very same levels of spatial and single-phase/multiphase complexity are valid when investigating an unsteady problem such as the mentioned pump-startup procedure. As opposed to the drilling-ahead case, in a pump-startup procedure, ideally only an initial cuttings bed might be present.

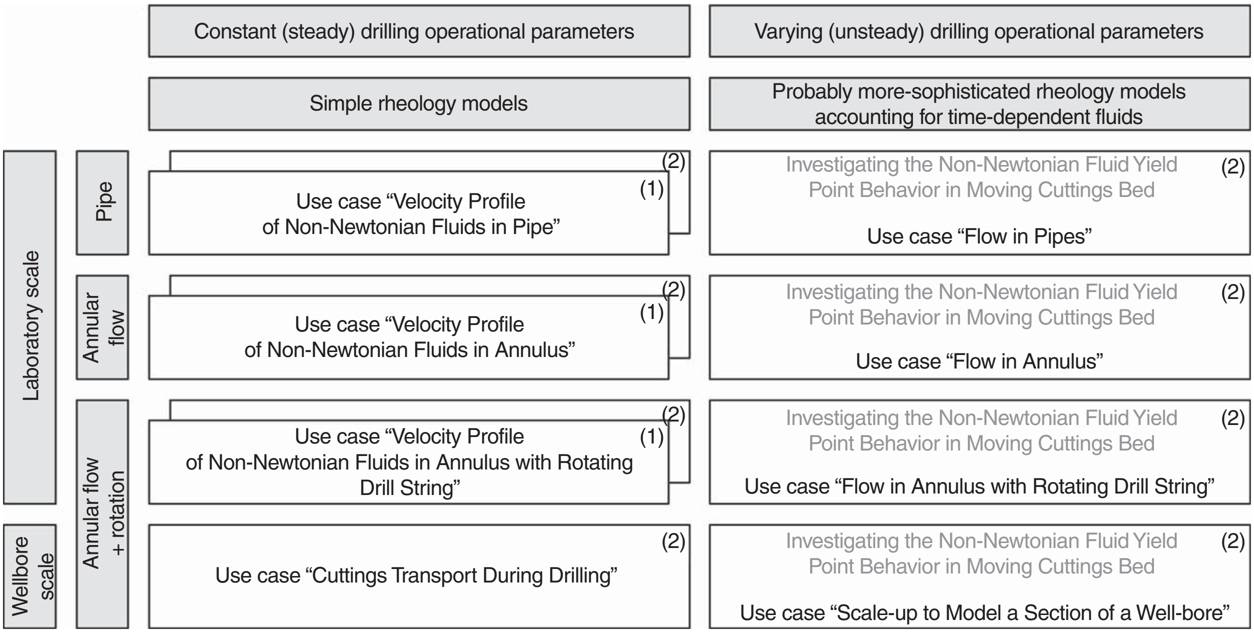

Fig. 11—Use cases defined for cuttings-transport modeling[15]: (1) plain mud (single-phase flow); (2) mud and cuttings (multiphase flow).

Parameterization of the use cases presented in Fig. 11 may now be conducted using the values of characteristic ranges provided in Table 3.

Discussion

The proposed methodology allows a specification of a set of parameters for a wellbore subsection. This is not straightforward, because in some cases a direct link between a tophole parameter such as hookload and a corresponding bottomhole parameter cannot be established. However, it is shown that a set of parameters describing a wellbore tophole is not sufficient to describe a specific wellbore subsection because the lists of parameters are not equivalent. Internal states and outputs of the wellbore description become inputs for the wellbore subsection.

Case-Parameter Sets. Numerical-value ranges for both the wellbore and wellbore-subsection scope are determined by exploiting aggregated wellbore data of the NPD.

Possessing more-sophisticated (consistent and comprehensive) aggregated data would potentially yield a more-precise value range for respective parameters and drilling operations and procedures. The numerical values provided for the individual parameter sets are dependent on various assumptions using partly inaccurate or insufficient data. Establishing characteristic parameter-value ranges is, for instance, purely dependent on MD caused by lack of accessible TVD cases. However, the error seems to be small because most wells in the exploration database feature a fairly low MD/TVD ratio (MD/TVD $\leq$ 1.2 for more than 95% of all wells) **(Fig. 12),** indicating that in most cases MD is fairly close to TVD.

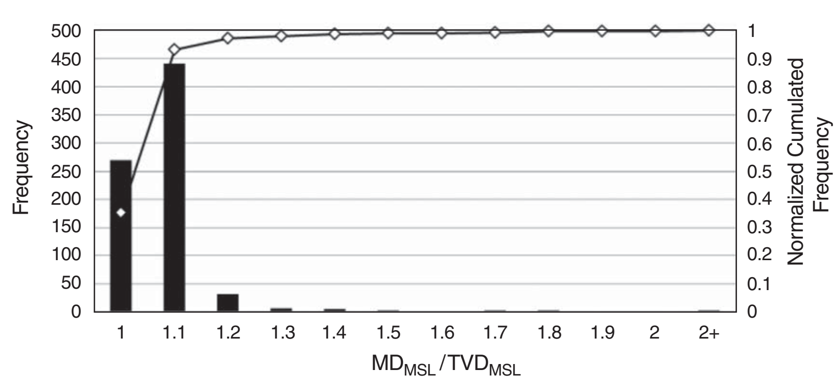

Fig. 12—MD/TVD ratio distribution of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM (NPD 2015).

[15]Derived from Simonsen, A. and Meese, E. A. 2015. AdWell Milestone E2–Guidelines and Concepts for CFD Modelling. Project report. Trondheim: SINTEF Materials & Chemistry.

The obtained characteristic parameter ranges are dependent on various simplifying assumptions, mainly limited with respect to accessibility of data. Particular examples are the following:

- Operation: We have focused on conventional drilling. This complies only to some extent with the data we have used. Extended-reach operations (MD/TVD > 2) do not seem to be part of the data, as indicated by Fig. 12. The cases of HP/HT operations, however, were excluded on the basis of bottomhole temperature (<150°C) only because the data do not contain any information about downhole pressure.
- Inclination: We have not distinguished between vertical, intermediate, and highly inclined wells because the majority of wells in the exploited exploration database are fairly vertical **(Fig. 13).** By including the development-well database, one could potentially gain a more-specific picture with regard to well inclinations.
- Temperature: In case of bottomhole temperature, we have not distinguished between different geological sections of the NCS. It seems more appropriate to divide the NCS into different sectors and establish a respective-temperature relationship, as indicated in Fig. 7.
- Rock properties: By categorizing the NCS into different sectors, it is possible to narrow down rock properties (i.e., cuttings density and porosity). Here, further information from oil companies and other public databases is required.
- Mud type: The subset of data used does not fully represent all WBM cases because of data quality. The available data do incorporate a mixture of mud categories and brand names but no information on mud types. We have only considered data where the mud type is clearly identifiable as WBM.
- Mud rheological properties: We have based our parameter specification on PV and YP, which corresponds to the Bingham rheology model. To provide an approximate range of relevant rheological properties, the Bingham model may be sufficient. However, PV and YP are generally insufficient to provide an appropriate picture of mud rheological properties and are in particular not suited for modeling purposes (Hemphill et al. 1993). Although one can obtain corresponding power-law- or Herschel-Bulkley-model coefficients from PV and YP [e.g., through American Petroleum Institute definitions (*API RP 13D* 2010)], these become very rough approximations. Ideally, a more-sophisticated rheology model such as the (unified) Herschel-Bulkley model (Zamora and Power 2002; *API RP 13D* 2010) should be used.
- Hookload: It is considered as an internal state and block position and/or the speed of the drillstring are considered input variables on the wellbore level. Further investigation seems required for how these input parameters and internal states relate to a specific parameter used in experimental or virtual cuttings-transport modeling on the wellbore-subsection level and how they exactly affect cuttings generation and buildup, or vice versa.

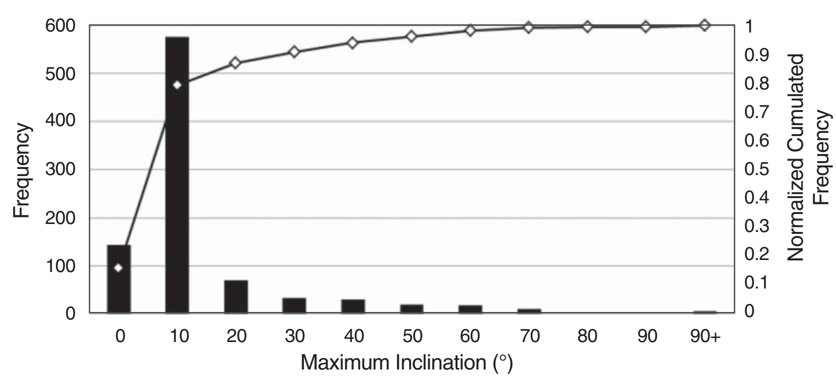

Fig. 13—Inclination distribution of NCS exploration/appraisal wells drilled between 1967 and 2015, bottomhole temperature < 150°C, mud type = WBM (NPD 2015).

The actual availability of (aggregated) data is an issue, as highlighted previously. Furthermore, replication of hole cleaning for a particular well with RT models requires RT data (upper level of Fig. 1). In case of long directional wells, the accuracy of directional measurements may be poor. Data for cuttings properties and flow rates are not normally available. Drilling-fluid measurements are usually accessed through the drilling-data report of the operator or the drilling-fluid report of the mud supplier and are not normally streamed in RT, although there is a current focus on automation of such systems (Iversen and Geehan 2015).

The case-parameter-value ranges established in this study are derived from normal operational data. To pinpoint the most-critical case-parameter configurations, a cuttings-transport-problem database may prove beneficial [similar to the NPD fact pages, but only containing problematic (in the sense of hole-cleaning) case parameters]. These parameter sets may be provided anonymously by drilling companies, without disclosing confidential company drilling data, as an input to the proposed database, which would be open to the scientific community. Cuttings-transport-modeling studies could then be conducted using these industry-relevant parameter sets, hereafter termed benchmarks. The study results would be fed back into the database and would be accessible for further research and meta-analysis.

Comparison With Recent Cuttings-Transport Studies. The benchmarked studies feature parameter values that are only partly within our derived intervals.

None of them have worked with the exact same geometry we have used to derive our parameter sets. However, most studies have used very similar hydraulic diameters (0.079, 0.089 m). As mentioned previously, in some cases rheological properties are not directly comparable because different models were used. It seems reasonable that despite a common hydraulic diameter, other values are not coinciding with our intervals because the general purpose is to investigate cuttings-transport problems. In that sense, a mud-flow rate lower than our specified interval seems of higher interest. Interestingly, many studies have used a fairly moderate ROP and therefore a lower cuttings-flow rate than we have estimated. The cuttings-mass-flow rate is mainly dependent on Eq. 1, but the effect of porosity seems not to be considered. Another aspect is mud density being in general on the very low end of our derived characteristic range. This might be caused by laboratory restrictions, such as laboratory fluids being mainly derived from water without any weighting additive.

For comparison of results and to conduct a quantitative meta-analysis, a scaling methodology is required, applying relevant parameters and our best physical understanding. Apparently, very few cuttings-transport studies actually seem to have nondimensionalized the respective problem of interest (Luo et al. 1992; Li and Walker 2001; Kelessidis and Bandelis 2004; Ozbayoglu et al. 2007), all of which have made use of a Newtonian viscosity.

The different parameter sets applied clearly demonstrate the value of including reference-parameter sets in a shared benchmark database.

Use Cases. The use cases presented in this paper represent a very small subset of all potential use cases. Referring to a particular drilling operation and procedure enables one to determine characteristic parameter ranges and establish specific use cases. All use cases presented are specified with regard to a laboratory scale, which in the provided example is equal to the wellbore-subsection scale. However, this is not necessarily always the case. For instance, one might not be able to work with the very same spatial dimensions (annular and pipe diameter, length), fluids, or temperatures. In such cases, an adequate scaling concept is required to scale down the defined wellbore-subsection-parameter ranges to a laboratory setup if needed. To the authors' knowledge, a comprehensive cuttings-transport-scaling concept accounting for non-Newtonian fluid behavior and temperature does not currently exist.

Again, the existence of a database would help to unify cuttings-transport-modeling activities with regard to the different complexity levels.

Benchmarks. In this paper we provide a simplified example of how case-parameter sets for cuttings-transport research can be established. If established on a more generic and sophisticated basis (addressing different drilling operations and procedures, regions, well profiles, and mud types, and dependent on more-accurate aggregated data) and combined with case sets of experimental and drilling data, publicly available benchmarks using the previously mentioned database might help improve effectiveness and efficiency in wellbore-transport research:

- **Effectiveness:** Because the benchmarks/parameter sets would cover the industry's currently most-used and most-challenging operating points with respect to cuttings transport, the industrially relevant problem in terms of parameter domains would be investigated in each study.
- **Efficiency:** Because the benchmarks/parameter sets would be available to the research community upfront, a faster startup of new projects as well as straightforward benchmarking and validation of results could be performed.

Conclusions

This paper presents parameter sets and use cases along with specified parameters with a focus on the NCS. Use cases with case-parameter sets presented might serve as a reference for experimental and virtual modelers in a cuttings-transport-research project to help ensure consistent work throughout the project. Across the project, these parameter sets are considered to serve as benchmarks to standardize research efforts. In addition, the following recommendations and conclusions may be drawn:

1. Disclosure of parameters: The parameters summarized in Fig. 5 and Table 3 are regarded as essential when specifying any cuttings-transport problem, and their numerical values should be fully and comprehensively disclosed in any publication. Additional research-method-dependent parameters, as briefly described in the subsection Research-Method-Specific Parameters, should also be fully disclosed to enable repetition of the study. Furthermore, it might be of value to additionally provide the most-important nondimensional numbers characterizing the investigated problem (i.e., Reynolds number, particle Reynolds number, and Stokes number). The applied definition of the nondimensional number should also be provided.
2. Description of rheological properties: Further development of benchmarks as suggested in this paper should make use of both a comprehensive and a more-sophisticated rheology model (e.g., the Herschel-Bulkley model). Studies should ideally disclose the actual rheological data in addition to model coefficients because of the diversity of mud rheological properties used in drilling.
3. Need for comprehensive scaling concept: A holistic scaling concept, dependent on physically sound nondimensional numbers, which incorporates all parameters relevant to cuttings transport and accounts for non-Newtonian fluid properties seems to be required.
4. Relevance and effect of parameters: Further research to clarify the relevance and effect of parameters such as pressure on rheology, or the effect of cuttings transport on hookload, seems necessary.
5. Reference-parameter-sets database and benchmark cases: The development of a database containing anonymized critical parameter sets of the industry's most-relevant cuttings-transport problems, ideally together with respective anonymized experimental and/or field data, seems very beneficial for further hole-cleaning research. The drilling industry could gain both efficiency and effectiveness if standard parameter sets for modeling purposes were publicly available to researchers because this would result in focusing on the industry's most-used and most-challenging operating points as well as a faster project startup and straightforward comparison and validation of results.

Nomenclature

A = system matrix
B = input matrix
C = output matrix
d = bit/hole diameter, L, in.
$f(\ldots)$ = functional of …
$h(\ldots)$ = functional of …
t = time, t, seconds
u = process inputs
v = measurement noise
$\dot{V}_{out}$ = cuttings flow rate, L^3/t, L/min
w = process noise
x = internal states
$\dot{x}$ = time derivatives of internal states
y = measured outputs
ϕ = porosity, L^3/L^3, –

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SI Metric Conversion Factors

$^\circ C + 273.15$	$E+00 = K$
in. $\times$ 2.54*	$E-02 = m$
L/min $\times$ 1.667	$E-05 = m^3/s$
m/h $\times$ 2.778	$E-04 = m/s$

*Conversion factor is exact.

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