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Monitoring Hole-Cleaning during Drilling Operations: Case Studies with a Real-Time Transient Model

Pedro J. Arévalo, Matthew Forshaw, Alexander Starostin, Roger Aragall, and Sergiy Grymalyuk, Baker Hughes

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Abstract

Steady-state hole-cleaning models used to monitor cuttings during well construction rely on static parameters that portrait specific drilling scenarios disconnected from each other. This paper presents the integration of transient hole-cleaning models validated in the field into a digital twin of the wellbore deployed while drilling. Thus, enabling the monitoring of the evolution of cuttings, which reduces uncertainty around the state of hole-cleaning procedures and minimizes the associated risk.

A digital twin of the wellbore equipped with physics-based transient models is prepared in the planning phase, and later deployed to a real-time environment. While drilling, smart triggering algorithms constantly monitor drilling parameters at surface and downhole to automatically update the digital twin and refine simulation results. The physics-based transient model continuously estimates cuttings suspended in the drilling mud and cuttings deposited as stationary beds, which enables evaluation of cuttings distributions along the wellbore in real time. Automation systems consume the predicted results via an aggregation layer to refine fit-for-purpose hole-cleaning monitoring applications deployed at the rig.

The transient hole-cleaning model has been integrated into digital twins used during pre-job planning as well as in real-time environments. The system deployed in real-time successfully tracks the state of cuttings concentration in the wellbore during all operations (drilling, tripping, off-bottom circulation, connections) considering the effects of high-temperature and high-pressure on the drilling fluid. Moreover, since the model uses previous results as starting point for the next estimation cycle, it creates a dynamic prediction of how the cuttings evolve while drilling. Fit-for-purpose automation and monitoring services predict drilling issues related to hole-cleaning, downhole pressure, among others. Drillers and drilling optimization personnel receive actionable information to mitigate hole-cleaning issues and avoid detrimental effects for operations. The user interface (UI) presents how the cuttings distribution change with evolution of input parameters (rate of penetration, string rotation, and flow rate).

A set of case studies confirm the effectiveness of the approach and illustrate its benefits. One case study from the North Sea illustrates the reaction of the model to changing operational parameters, while another combines along-string-measurements of density with the cuttings predictions to confirm the trend established by the predicted cuttings concentration.

Introduction

The cost of wellbore construction contains a non-productive time (NPT) component that can be as high as 30% of the well construction capital expenditure (CAPEX) (Forshaw et al. 2020). A significant portion of such NPT events are related to poor management of cuttings transport, which leads to excessive accumulation of cuttings inside the wellbore. Cuttings beds can cause severe problems downhole, such as pack-offs leading to sidetracks, lost in hole (LIH) equipment, or both. Common practices to avoid such issues include a combination of empirical practices and reactive monitoring to maintain wellbore stability. An example of the first kind is the circulation that takes place after drilling each stand. Despite being a good practice, the amount of time and repetitions required to achieve a clean wellbore is based on experience and it is common for operators to spend more time circulating to clean the wellbore than is necessary. This is a form of invisible lost time (ILT). An example of the second kind of practice is to constantly monitor the pressure and hookload on surface to identify pack-offs and set downs. In such cases, there is no prevention or prediction of the drilling dysfunctions, but rather an identification of the issue when it takes place.

Consequently, in addition to following good drilling practices and implementing data-driven monitoring applications, there is the need of a complementary system that can reduce the uncertainty associated with the management of cuttings transport. This is the role of physics-based models deployed while drilling (Zamora et al., 2000; Sahri et al., 2018; Chmela et al., 2014; Porter et al., 2019, Arévalo et al. 2021).

A physics-based model, also labeled as a digital twin, portraits a representation of the wellbore and its reaction to different downhole scenarios. Traditionally, such digital twins are steady-state models that depict the concentration of cuttings in the wellbore by using a specific downhole scenario as input. As such, steady-state models can only deliver snapshots of the distribution of cuttings in the wellbore without any connection between subsequent snapshots. Transient models, on the other hand, connect adjacent simulations to create a dynamic monitoring of the cutting concentration in the wellbore. The automation system described in this paper integrates a drift-flux hole-cleaning model deployed in real-time to monitor the distribution of cuttings in the wellbore under all types of operations (drilling, circulating, making connections, etc.). Furthermore, the automation system integrates third party sensors to enrich the data representation and validate the results.

Drift-Flux Cutting Transport Model

Physics-based models of cuttings transport in the wellbore must consider how cuttings behave within the drilling fluid under a variety of scenarios. These include production of particles while drilling; suspension of particles in the annular flow column; deposition of particles to form beds in the wellbore; and erosion of cuttings beds transforming stationary particles into suspended ones in the column of drilling fluid. The drift-flux cutting transport model that is the center of the advisory system presented in this work is derived from the Navier-Stokes equations for a Hershel-Buckley fluid. A more detailed description of the model and its implications are presented in Starostin et al. 2022, Forshaw et al. 2022 and Aragall et al. 2022.

The transient hole-cleaning model has been validated in collaboration with operators in the North Sea and the Middle East to corroborate its accuracy and benefits. The validation has been performed directly and indirectly. The direct validation compares the measured cuttings return with the modeled output volume (Figure 1).

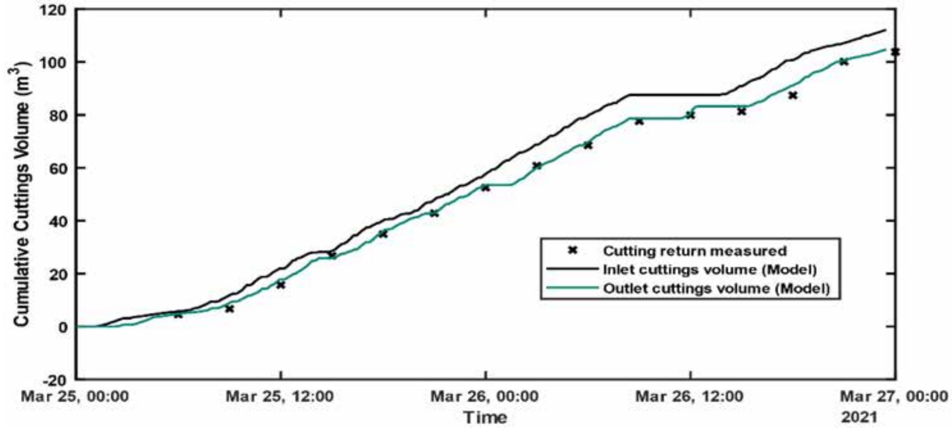


Figure 1—Direct validation: Comparison of measured and modeled cuttings return (Starostin et al. 2022)

It can be observed that the model output volume has a good agreement with the measured cuttings return, which enables tracking of time delay between cuttings generation and return (bottom-up time). Indirect validations can be performed by comparing variables that are easier to measure and that are dependent of the output of the transient hole-cleaning model, such as equivalent circulating density (ECD) while drilling. In this case, the modeled transient ECD is compared to actual density measurements from pressure while drilling (PWD) services deployed while drilling (Figure 2).

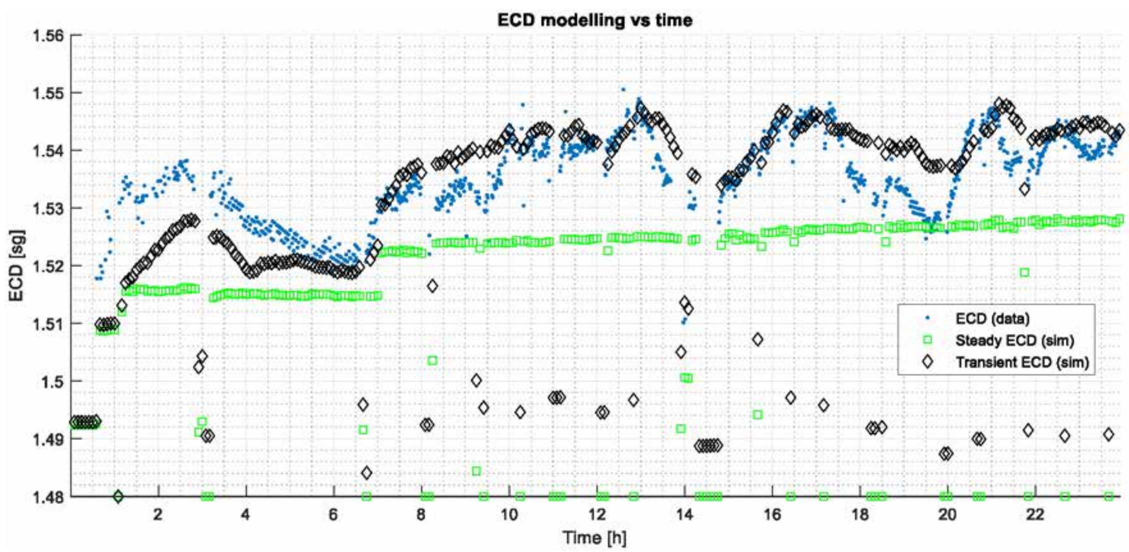


Figure 2—Indirect validation: Comparison of measured and modeled downhole ECD (Starostin et al. 2022)

The comparison includes steady state and transient hole-cleaning models used as inputs for the calculation of ECD downhole. The modeled transient ECD has a good match with the downhole ECD. On the other hand, the modeled steady-state ECD follows the average trend of the density in the wellbore but it fails to depict the variations in real-time.

Overall, both forms of validations have been successful and consequently, a complete service has been built around the transient hole-cleaning model deployed in real-time. Currently, the advisory hole-cleaning service is deployed globally and its validation with a regional focus continues.

Hole-Cleaning Advisory Service

The system components required to deploy the proposed approach are pre-job modeling remote or on premise, real-time application (RT) at the rig site, data acquisition system at the rig site, and automation application deployed at the rig site and visualized either on premise or remotely (Figure 3). The communication across components deployed at the rig-site is achieved via a data aggregation layer that enables multi-point data transfer. Furthermore, the use of a data aggregation layer increases the scalability and flexibility of the system and reduces the dependencies between system components. A more detailed description of the system deployed in real-time is presented in Arévalo et al. 2021.

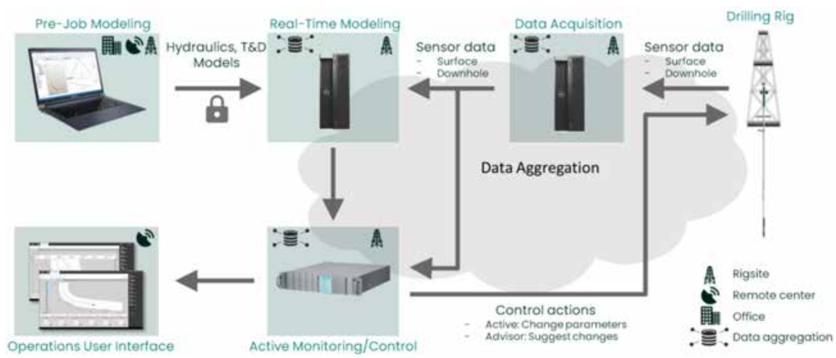


Figure 3—Overview of system components: Data flow schematic

The workflow starts in the pre-job modeling phase, where a fit for purpose physics-based transient model of the wellbore or *run plan* is prepared. The run plan contains expected lithology, geomechanics and operational parameters for the upcoming run. It delivers a wide variety of hydraulics, torque & drag, advance mechanics, magnetic interference, pressure regime and hole-cleaning simulations among others. For the case of the hole-cleaning workflow, the modeling application estimates the distribution of cuttings in the wellbore, the required fluid velocity to transport cuttings to surface, and the time to transport cuttings to surface using the current operational parameters (Figure 4). Furthermore, the model integrates the cuttings distribution into the calculation of other hydraulics outputs, such as the equivalent circulating density (ECD), equivalent static density (ESD) and modeled standpipe pressure (SPP).

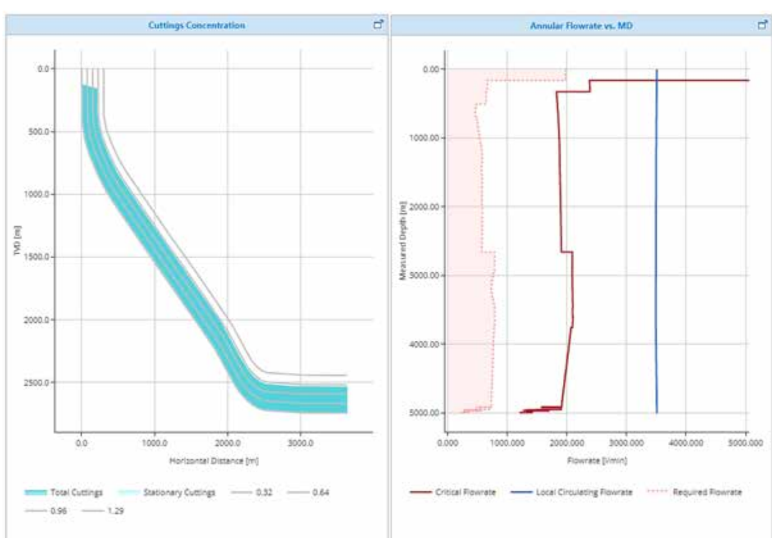


Figure 4—Hole-cleaning results produced in the pre-job modeling application Left – Cuttings concentration. Right – Annular flow rate

Afterwards, the run plan is transferred to a real-time environment via a secured connection where the same physics-based digital twin used in the pre-job modeling phase is now deployed while drilling. Smart-triggering algorithms monitor the input sensor data to determine when to update the models with live sensor data. The use of smart-triggering algorithms accomplishes two main objectives: produces relevant results and avoids the overhead of running all simulations periodically. Instead, the different simulations run only when an update of the results is relevant.

The run plan deployed in real-time considers a hybrid set of input data (Forshaw et al. 2019, Taugbøl et al. 2021), since some parameters are considered as static (e.g., drill string, rig equipment), while other change in real-time (e.g., rotation speed, bit depth). Figure 5 illustrates the execution cycle in real-time and the combination of input data used by the models.

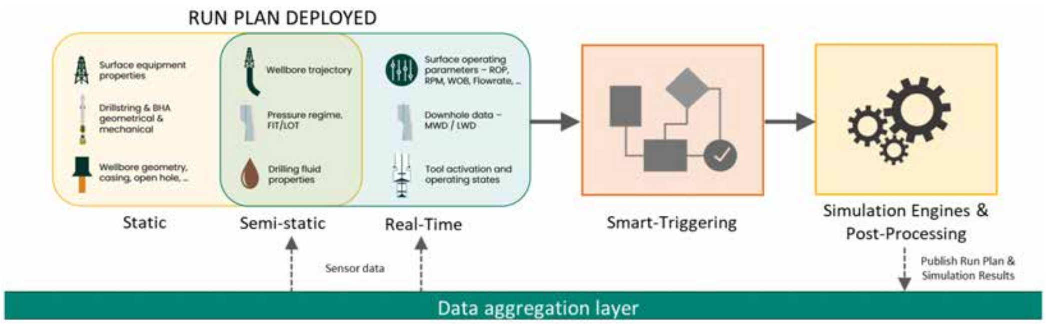


Figure 5—Real-time execution (Arévalo et al. 2021)

The drilling fluid properties required when running the digital twins in real-time can be provided in different deployment scenarios to accommodate existing worldwide setups. The most accurate is the usage of automated fluid monitoring (AFM) units that provide frequent updates of the drilling fluid properties to enable accurate tracking of the cuttings distribution as well as the density in the wellbore. Nevertheless, most deployments around the world still rely on periodic reports of density and rheology, which are less frequent than the measurements from AFM units. This scenario is also supported by the real-time drilling engineering application, which enables users to select an alternative data source to provide manual updates of drilling fluid properties.

For the case of hole-cleaning simulations, each model execution considers the last estimated distribution of cuttings in the wellbore and the current operational parameters to estimate the current spatial distribution of cuttings. The continuous deployment of such a model permits dynamic monitoring of the cuttings transport from creation of the particles until its transport to surface. Figure 6 presents a summary of the inputs and outputs produced by the model in real-time.

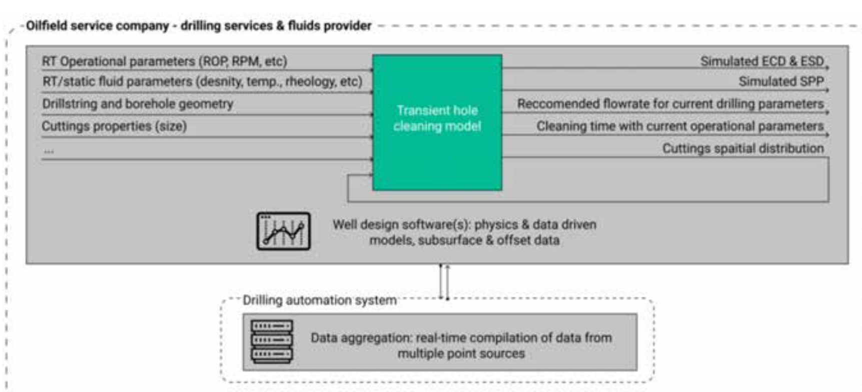


Figure 6—Inputs and outputs of transient hole-cleaning model in real-time (Forshaw et al. 2022)

The last stage in the workflow is active monitoring and control, which is the task of automation applications deployed at the rig site. Such applications consume the drilling engineering results produced in real-time to fuel fit-for-purpose monitoring and control services, such as the hole-cleaning advisory system presented in the figures below. Figures 7 represents the most common deployment scenario of the automated hole cleaning advisor worldwide, while the scenario illustrated in Figure 8 has the added value of having pressure sensors distributed along the string to validate trends. In both cases, the user interface is nearly the same facilitating deployment and seamless switching between scenarios.

Figure 7—Automated hole-cleaning monitoring service (Forshaw et al. 2022)

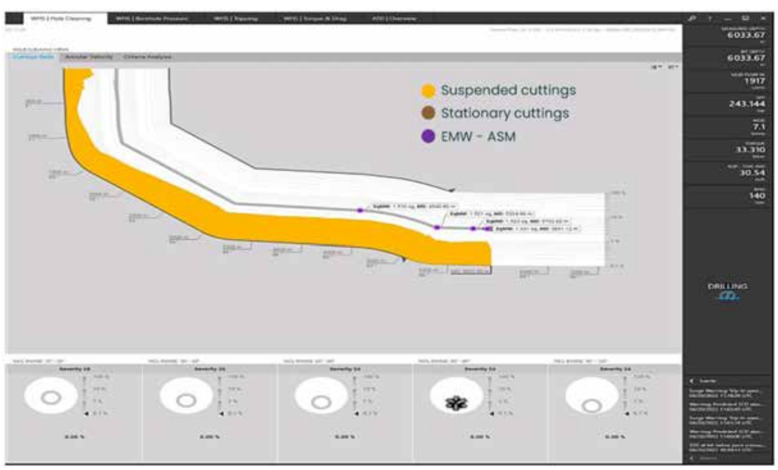


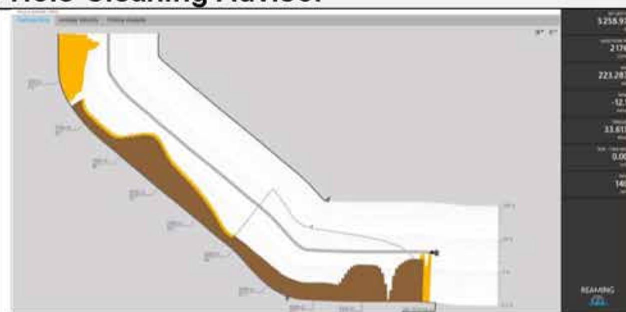
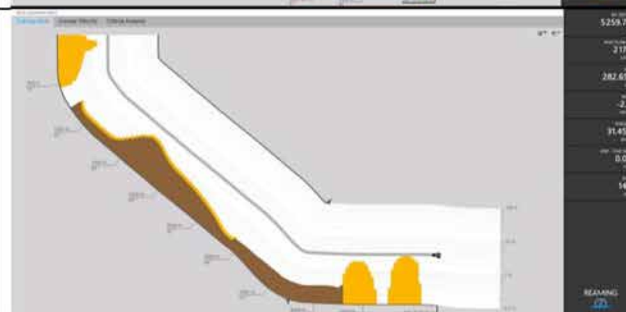
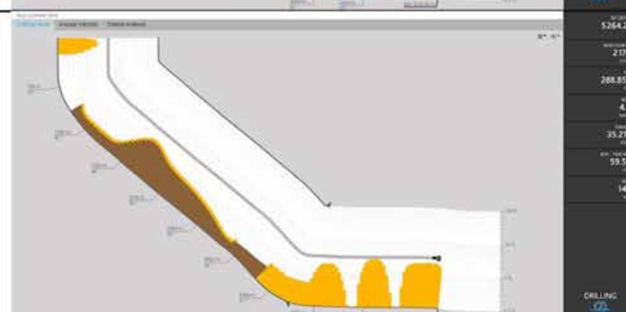
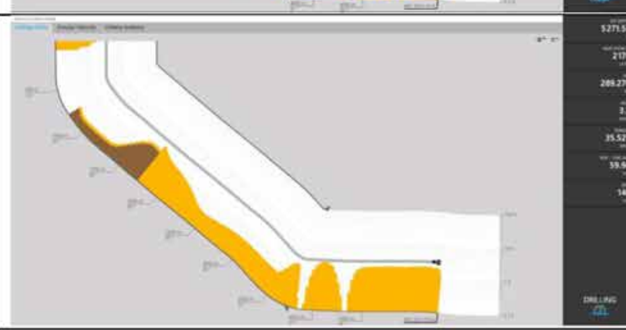
Figure 8—Automated hole-cleaning monitoring service including along-string pressure measurements

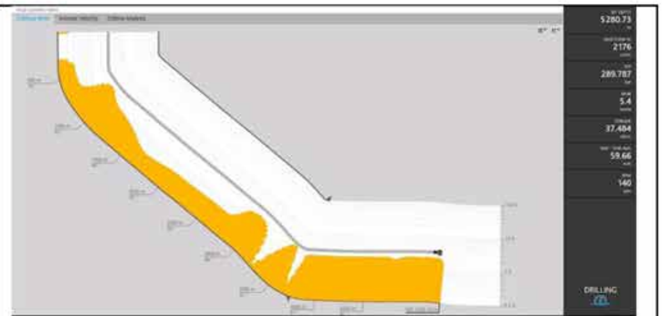
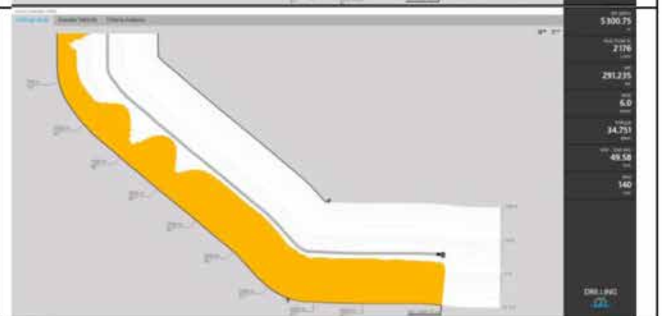
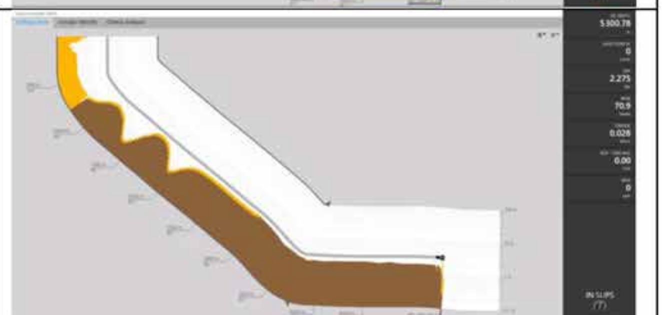
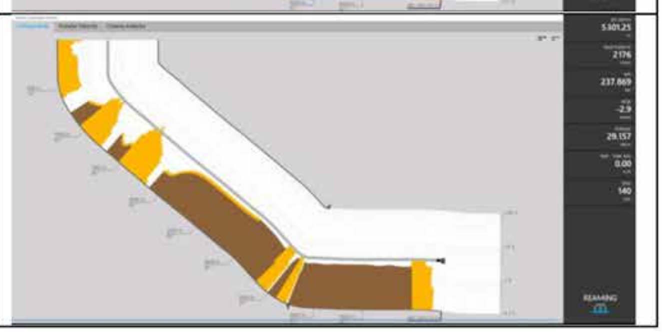
The hole-cleaning service presents to the user the results of the continuous deployment of the drift-flux cuttings transport model and simplifies understanding of the influence of operational parameters in the creation, deposition, suspension, and further transport of particles to surface. The proposed approach to actively estimate and track the concentration of cuttings in the wellbore has been deployed around the world proving its validity. One of the most active regions using the transient hole-cleaning model is the North Sea, where multiple rigs are equipped with AFM units to provide frequent measurements of the drilling fluid's properties to enhance the output of the hydraulics models used in real-time. Two case studies from this region are presented next to highlight the positive feedback obtained from operations.

Case Study: Deployment of a Transient Hole-Cleaning Model in Real-Time

This case study presents a drilling run in the North Sea with focus on one stand taken as an example to illustrate the reaction of the drift-flux cuttings transport model to the changes in operational parameters. Below, a series of images in Table 1 present the updates of the UI in response to changes in surface operational parameters. In this case, the hole-cleaning advisor estimated a minimum flow rate to transport cuttings to surface of 1758 l/min during the stand. All scenarios with flow rate higher than the minimum will contribute to the erosion and suspension of cuttings in the drilling fluid for transport to surface.

Table 1—Response of Transient Hole-Cleaning to Parameter Changes

Scenario	Result	Hole-Cleaning Advisor
Circulation off-bottom. Flow rate = 2176 l/min **Depth = 5259.86 m** Bit Depth = 5258.97 m ROP = 0 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	Suspended cuttings transported to surface. Cuttings beds undergoing erosion.	
Circulation off-bottom. Flow rate = 2176 l/min **Depth = 5259.86 m** Bit Depth = 5259.78 m ROP = 0 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	Suspended cuttings transported to surface. Cuttings beds undergoing erosion	
Drilling: Start stand Flow rate = 2176 l/min **Depth = 5264.21 m** ROP = 59.54 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	New suspended cuttings produced at the bit. Older suspended cuttings transported to surface. Cuttings beds undergoing erosion	
Drilling: Erode cuttings beds Flow rate = 2176 l/min **Depth = 5271.53 m** ROP = 59.94 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	New suspended cuttings produced at the bit. Older suspended cuttings transported to surface. Cuttings beds undergoing erosion	

Drilling: No cuttings beds Flow rate = 2176 l/min **Depth = 5280.73 m** ROP = 59.66 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	New suspended cuttings produced at the bit. Older suspended cuttings transported to surface. Cuttings beds removed.	
Drilling: End of stand Flow rate = 2176 l/min **Depth = 5300.75 m** ROP = 49.58 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	New suspended cuttings produced at the bit. Older suspended cuttings transported to surface. No cuttings beds.	
Connection Flow rate = 0 l/min **Depth = 5301.26 m** Bit Depth = 5300.78 m ROP = 0 m/h RPM = 40 rpm	Suspended cuttings settle and most become cuttings beds.	
Circulation off-bottom. Flow rate = 2176 l/min **Depth = 5301.26 m** Bit Depth = 5301.25 m ROP = 0 m/h RPM = 140 rpm Flow rate higher than minimum to transport cuttings to surface.	Suspended cuttings transported to surface. Cuttings beds undergoing erosion	

In addition to updating the cuttings concentration on the user interface and suggesting the minimum flow rate to transport cuttings to surface, the hole-cleaning advisor also provides an estimation of time to clean up the wellbore with the current operational parameters. In this context, the operator can define a clean wellbore in terms of percentage of cuttings removed from the wellbore. Furthermore, as shown in the bottom of Figure 7, the hole-cleaning advisor segments the wellbore in inclination ranges to show cuttings accumulations in cross-sections. All of these features are complemented with event-alarm capabilities that maintain the user informed about potential excessive concentrations of cuttings in the wellbore, highlighting where the concentration takes place.

Overall, the deployment of transient hole-cleaning models validated in the field at-scale gives confidence to operations to optimize conventional hole-cleaning practices and reduce the amount of time invested in circulating the wellbore, hence reducing ILT.

Case Study: Integration of Along-String-Measurements

The most common deployment scenario for transient hole-cleaning models uses conventional drill pipe and mud reports providing drilling fluid properties at periodic but non-frequent updates. However, there are other less common scenarios, where the value proposition of the service is greatly enhanced by additional technologies, such as using automated fluid monitoring units, or incorporating pressure sensors along the string. This case study illustrates the integration of pressure sensors deployed in a wired-pipe string into the hole-cleaning advisory service.

Two consecutive drilling runs are used in this case study to illustrate the integration of ASM data into pressure monitoring and hole-cleaning services. The drilling runs take place in the North Sea, where 4 pressure sensors are deployed along the wired-pipe string, in addition to the PWD service using a pressure sensor in the BHA, which provides 5 real-time sensors for the monitoring of pressure downhole. The sensors used for monitoring are presented in Table 2.

Table 2—Response of Transient Hole-Cleaning to Parameter Changes

Downhole Sensor	Offset to the bit
ASM4	1392.04 m
ASM3	607.89 m
ASM2	197.58 m
AMS1	39.28 m
PWD	6.27 m

The sensors are integrated to the data aggregation layer via an adapter on surface that establishes a secured communication with the automation system hosting the hole-cleaning service, among others. Figures 9 and 10 below present the visualization of ASM equivalent mud weight as part of the borehole pressure monitoring service, which uses the results of the transient estimation of cuttings in the wellbore.

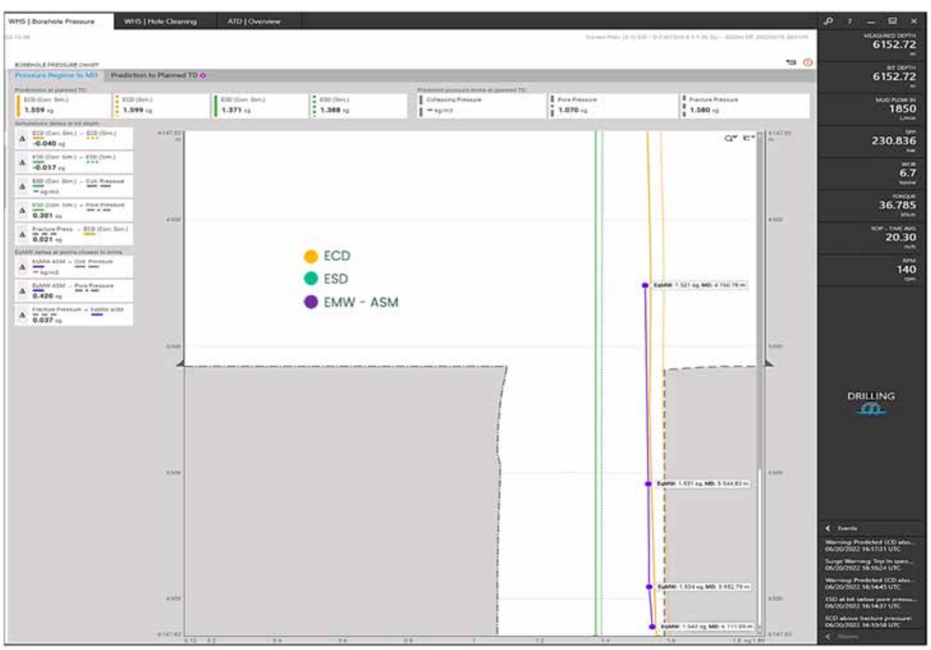


Figure 9—Wired-pipe EMW data integrated into borehole pressure service

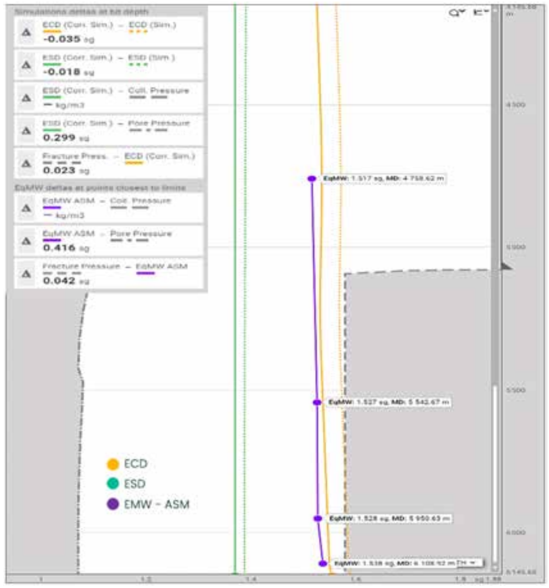


Figure 10—Wired-pipe EMW data integrated into borehole pressure service: Zoom in to highlight ECD trends and deltas to formation gradients

The EMW measured by the ASM sensors (1.538sg @ 6108m, 1.528 @ 5950m, 1.527sg @ 5542m, 1.517sg @4758m) present a similar trend to the transient modeled ECD (yellow profile), as presented in Figure 10. This serves as an indirect validation of the drift-flux cuttings transport model, since its results directly influence the estimation of density downhole (ESD, ECD). Figure 10 presents a zoom in on figure 9 to highlight the ECD and EMW trends. In addition, the top left side exhibits the difference between the formation gradients and the real-time measurements, and between formation gradients and estimation results. Such deltas serve as monitoring proxy for the pressure downhole.

In addition to the borehole pressure service, the hole-cleaning monitoring service includes the data from ASM sensors to enrich its presentation of results, as illustrated by Figures 11 and 12. The integration of ASM data allows for confirmation of potential tight spots while drilling caused by the accumulation of cuttings in the wellbore. The current example exhibits a concentration of only suspended cuttings with a flow rate high enough to transport them to surface. Therefore, the density measurements of all ASM sensors vary mainly due to their position along the string (depth).

Figure 11—Wired-pipe EMW data integrated into hole-cleaning service

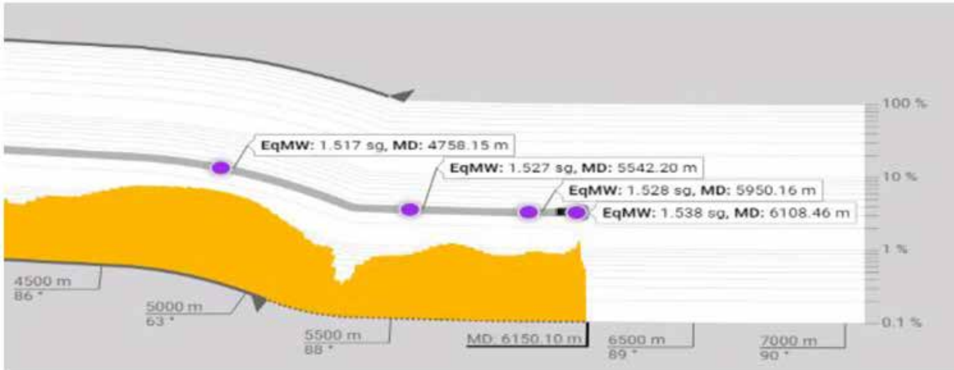


Figure 12—Wired-pipe EMW data integrated into hole-cleaning service: Zoom in on ASM results

Conclusions & Future Work

The proposed method deploys transient models in real-time that assess the hole-cleaning condition of the wellbore continuously and automatically thanks to smart triggering algorithms and real-time sensors. The outcome increases the ability of monitoring applications to both predict and react to potential drilling risks related to poor hole-cleaning, thus avoiding costly corrective actions for operations. The integration of transient modeling in real-time opens a variety of opportunities towards automation and optimization of procedures, such as reduction of ILT when circulating and identification of tight spots caused by excessive accumulation of cuttings in certain regions of the wellbore.

Furthermore, the drift-flux model used has been validated in different regions in collaboration with customers. The model reacts to changing parameters in surface and updates the grid that tracks the spatial distribution of cuttings in the wellbore, which simplifies understanding of the behavior of the particles while drilling and circulating.

Additionally, the system infrastructure that enables the deployment of such transient models allows for simple integration of external data providers that enrich the service, such as wired-pipe sensor data or AFM units. The integration of wired-pipe data into existing services contributes to explore new value propositions for the oil and gas drilling industry.

Down the road, there are some learnings to implement to enhance the quality of the service, such as filtering input data to be more robust against external interferences. In addition, the implementation of monitoring and advisory services establishes a ground to expand the exposure of such services to provide automated control of independent processes. This is one of the crucial next steps in the development: to bring more monitoring applications into the active and closed-loop control arena.

Acknowledgements

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Nomenclature

AFM	Automated fluid monitoring
ASM	Along string measurements
ECD	Equivalent circulating density
ESD	Equivalent static density
EMW	Equivalent mud weight
ILT	Invisible lost time
MD	Measured depth
NPT	Non-productive time
PWD	Pressure while drilling

ROP	Rate of penetration
RPM	Revolution per minute
RT	Real-time
T&D	Torque and drag
TVD	True vertical depth
UI	User interface
WOB	Weight on bit

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