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# Uncertainty quantification for cuttings transport process monitoring while drilling by ensemble Kalman filtering☆

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ABSTRACT

The aim in this work was to develop a method to draw our conclusions for the uncertain quantities of interest in a real problem in oilfield, namely the cuttings transport problem, given the limited data available. The cuttings transport process is subject to disturbances and is influenced by various factors in a stochastic and uncertain manner. In addition, the drilling environment is very complex to understand fully, and to model efficiently and accurately. An experiment was conducted to monitor the process in real-time via time-series measurements of distributed pressure transducers along the drillstring. A mathematical model describing the dynamic process of cuttings transport is developed, which aims to capture the dominant characteristics of the process, without attempting to model reality perfectly; modeling and measurement errors are represented by uncertainties in model inputs, parameters, and states. The proposed model is described in detail, and is incorporated in the Bayesian framework (via ensemble Kalman filtering) to make our best estimate about the location and amount of cuttings transported along the wellbore in real time, given the available data. The estimations of the uncertain process parameters are described.



## 1. Introduction

Particles transport, whether of solids, gases or liquids, appears in numerous applications in chemical engineering, geology, fluid mechanics and biology, e.g., [1–3]. Monitoring particles transport in industrial applications often requires the description of the dynamic transport process and the interaction of the various phases involved in the process. This description is modeled with mathematical models, and a number of approaches has been presented in the literature for their development, e.g., [4–7]. There are open questions on how to model complex physical phenomena, and often these models go into great detail to do so (e.g., [7] considers the stress around the surface of particles), which may result in complex and computationally expensive models. However, in industrial applications, it is often the case that we wish to monitor in real time processes that are hard to model mathematically due to our insufficient understanding of the process and due to the presence of process uncertainties. Thus, we considered statistical inference to monitor the process, as it is desired to quantify the uncertainties of the parameters of interest in terms of a probability distribution. The quantified uncertainties on process parameters represent uncertainties in the estimations due to model and measurement inaccuracies, and uncertainties present in process parameters and inputs.

Cuttings transport in oilfield drilling falls under the category of particles transport monitoring. The amount and location of cuttings distributed along the wellbore can be an essential factor causing a number of problems while drilling. Inadequate cuttings removal and accumulation of cuttings in the wellbore can cause costly and lengthy drilling problems, like stuck drillstring, early drill-bit wear, reduction in rate of penetration, excessive torque and drag on drillstring, difficulties in logging and cementing, and difficulties running casings. There are many studies in the literature for understanding cuttings transport theoretically and experimentally. For example, experimental work was conducted in [8] to understand the impact of various factors such as drilling fluid viscosity, velocity, and hole inclination on cuttings transport, and experiments were conducted in [9] aiming at the understanding of phenomena involved in the erosion of a cuttings bed deposited at the bottom of a horizontal annular section of a wellbore. On the other hand, there is a long list of mathematical models in the literature that describe the cuttings transport process in vertical, inclined, and horizontal wellbore; there is a variety of different models, some of which consider the formation of a moving cuttings layer, a stationary cuttings layer, a suspended cuttings layer, or the interaction between the layers,

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and some models consider complex effects such as the effect of drillstring eccentricity on cuttings transport, e.g., [10–13].

The development of mathematical models to describe deterministically the cuttings transport process can be a very challenging task. The drilling process is subject to various uncertainties, and the physics involved in complex drilling environments are not fully understood. The cuttings transport process is subject to disturbances that are uncertain and stochastic (e.g., drillstring vibration while drilling); cuttings have different shapes and sizes (hence different drag and slip laws may apply for each particle); cuttings interact with each other, the wellbore walls, and the drillstring in a stochastic approach; the process inputs can be uncertain and stochastic; and so on. In addition, a number of process parameters are hidden and cannot be measured directly by sensors (for example the cuttings distribution and velocity along the wellbore are not observed directly), but instead, the drilling process is observed by time-series measurements of a small number of process parameters (e.g., wellbore pressure or inlet fluid flow or outlet fluid flow) that are partial or indirect observations of the process parameters of interest (e.g., distribution of cuttings, or gas along the wellbore).

The aim in this work is to develop a method to draw a conclusion for the uncertain process quantities of interest through a real problem in oilfield, given the limited data available. The problem considered is the estimation of the distribution of cuttings along a vertical or inclined wellbore. At the moment we are limited in the availability of data, but possibly not in the future. At the moment, the available data are pressures (obtained from eight transducers distributed along the drillstring), and flow (obtained from a flow meter at the inlet of the wellbore). The cuttings transport problem is a complex process, and the observability of the process is yet at question. With the availability of more data (e.g., data recording the amount of cuttings along the wellbore or a property related directly to the amount of cuttings), the work presented here has the potential to question the observability of the process, the suitability and validation of the model describing the cuttings transport process, and of the estimation technique used.

We formulate the monitoring of the cuttings transport process as an unsteady statistical inverse problem, and we make estimates on various unknown process parameters, such as the distribution of cuttings along the wellbore, friction factor, and velocity of cuttings. A model is proposed that aims to capture the dominant characteristics of the process. We do not attempt to model reality as precisely as possible; instead a number of model parameters are considered uncertain. This model is incorporated in the Bayesian framework via the ensemble Kalman filter (EnKF) [14,15]. The EnKF is an estimation technique which relies on simulation based inference and utilizes a linearization in the data conditioning, which make the EnKF computationally efficient for statistical inversion of high-dimensional hidden Markov models. Efficient solution to statistical inverse problems is an open research problem, and a variety of techniques have been studied in the literature. For example, see [16] for a comparison of surrogate and reduced-order modeling for the solution of large-scale inverse problems. In principle, given more data, the estimation method and the model presented can be extended, however we note that difficulties may be encountered that may have not been anticipated here, in which case modifications to the method and model may need to be developed.

The problem is formulated in Section 2. A physical model is presented in Section 3. The model aims to capture the dominant physics involved in the experimental setup, and it's implementation is provided in Section 4, where a first order upwind discretization scheme is described. In Section 5 we characterize model uncertainties, and provide a representation of the resulting probabilistic model. In Section 6 we incorporate the probabilistic model within the Bayesian framework, and provide a summary of the EnKF. In Section 7 we present the uncertainty quantification results given time-series measurements obtained from the distributed pressure sensors. Finally, conclusions are drawn in Section 8.

## 2. Problem formulation

The problem under consideration is the real-time quantification of the amount of cuttings along the wellbore from distributed pressure measurements. Distributed pressure measurements are partial and indirect observations of the amount of cuttings along the wellbore, however, they are informative, since pressure depends on the local density of the fluid-cuttings mixture, which is altered by cuttings as they travel along the wellbore. Conventional boundary measurements, such as flow-in and flow-out measurements, and a single boundary pressure measurement at the surface (standpipe pressure) do not capture adequate information to interpret the location and amount of cuttings along the wellbore in time; the effect of cuttings on stand pipe pressure is averaged over the whole wellbore. On the other hand, the evolution of cuttings along the wellbore is indirectly captured by the time-series measurements from distributed pressure sensors as cuttings move along the wellbore. We utilize along string distributed pressure sensors offered by the wired drill pipe technology. The wired drilled pipe technology is capable of handling a high bandwidth telemetry, and can be utilized for managed pressure drilling to maintain direction control and wellbore integrity [17]; it is a new technology not commonly used yet, and is more expensive, however, it provides distributed measurements along the length of the wellbore, which are very informative for the purpose of cuttings transport and multiphase flow monitoring.

Fig. 1 shows the schematic of the experimental set-up for the cuttings transport monitoring problem studied.

As cuttings are generated at the bottom of the wellbore, they are carried with the drilling fluid at surface. Cuttings are assumed to be in suspension, traveling at a velocity less that the drilling fluid velocity by an amount known as *slip velocity*. Slip velocity is approximately uniform along sections of the wellbore with the same diameter and inclination. In this experiment the wellbore section was uniform in diameter and it was vertical. As mentioned in the introduction, slip velocity in each section depends on various factors, like the shape of cuttings, the interaction of the drillstring with the cuttings, and the transport properties of the drilling fluid. We do not model deterministically the complex effects of these factors on the slip velocity. Instead, we consider the slip velocity

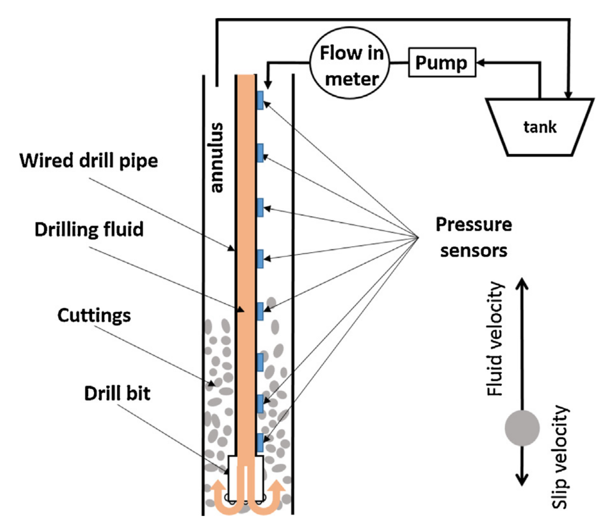


**Fig. 1.** Schematic of a wired drill pipe; sensors available are a set of distributed down-hole pressure transducers attached on the wired drill pipe, and surface flow-out and flow-in meter.