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Data clustering for model-prediction discrepancy reduction – A case study of solids transport in oil/gas pipelines

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ABSTRACT

The minimum fluid-flow velocity to ensure particle transport in pipelines is an essential design and operation consideration for oil and gas production. This flow velocity is difficult to estimate due to complex nature of the physical processes. It has been shown that the predictions of different, alternative models may vary several orders of magnitude for the same inputs. This paper introduces a systematic approach to reduce this discrepancy using data clustering, model selection, and cluster identification techniques. The approach is tested using 772 experimental data points (published in open literature), and the results show that the average of the error percentages between the predictions and experimental velocities are reduced from several orders of magnitude to 37%.

1. Introduction

The solid transport and management systems (STMS) are an integral part of the production facilities for the energy industries because solids are produced along with oil and gas from reservoirs on both onshore and offshore sites. These solids include sand or clay type particles and proppants, which are resin-coated sand or high-strength ceramic materials injected to the well to hold fractures open after the fracturing treatment ("Schlumberger Oilfield Glossary"). The STMS involve sand production control in the wells, the transportation of the produced sand to the surface facilities through the pipelines, and the separation of the transported sand at the surface facilities. The solids production control is achieved via selected well completions, e.g., gravel packs for complete exclusions, and via control of production rate from the wells to limit the amount of solids produced. Solids monitoring approaches are used to determine the characteristics of the produced sand, such as its density, size distribution, and its concentration in the well and pipelines. Before the sand can be separated from the produced fluids at the separators, it should be transported through the well and the pipelines by the produced fluids. At this stage, the flowrate of the produced fluids is adjusted to allow transport of the solids to the separators while keeping the erosion risk below design limits. Once solids reach separators, the separators are flushed on a regular basis based on the expected production rate of the solids. More detailed discussion of these systems can be found in (Mathis, 2003; Tronvoll et al., 2001). The safe and economical operation of these systems is crucial for continued competitive viability of the oil and natural gas production operations because of the problems that solids can cause. For example, accumulation of solids in the pipelines might result in under-bed corrosion and/or blockage of that line; or if the amount and velocity of the solids in the fluids (oil and gas) in the transportation lines are too high they might cause erosion in the pipelines resulting in facility integrity issues.

In STMS, one of the integral decisions is the fluid flow rate through the pipelines to minimize the solids accumulation, which requires the estimation of the minimum velocity required for the fluid for transporting produced solids. The determination of this minimum velocity, often referred to as threshold velocity, has been a great interest of the research community in order to efficiently and safely transport the solid particles in the hydraulic and pneumatic conveying systems. This velocity is dependent on the transport mechanisms involved. Over the last six decades, researchers have conducted experimental studies at various operating conditions using different materials in order to understand the fundamental solid transport mechanisms in fluids and to determine the effects of operating conditions and materials on the observed mechanisms. These experimental findings, in turn, provide the foundation for developing models to predict the threshold velocity and for improving their accuracies. In general, the experimental studies focus on understanding the effects of the fluid and particle properties, the pipe conditions and solid particle

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concentrations on the observed threshold velocity, because these variables have been shown to be critical factors that influence this velocity.

Predicting the necessary threshold velocity is difficult because of the complex mechanisms that have been observed in particle motion in fluids. Many forces are acting on the single particle such as drag force, friction force, and lift force. Moreover, the effect of particle-particle interactions becomes important as the solid particle concentration increases. A literature search on the models that are developed to predict threshold velocity for solids transport yields well over 60 models (Shin, 2013; Soepyan et al., 2014). As will be discussed in more detail in Section 2, there are many different velocity definitions for solids transport. For instance, Oroskar and Turian (1980) defined critical velocity as the fluid velocity that marks the transition from settling of solid particles at the bottom of the pipe to suspension of the particles; Hayden et al. (2003) classified pick-up velocity as the fluid velocity sufficient for initiating the motion of a solid particle at rest in a conduit; and Gruesbeck et al. (1979) defined equilibrium velocity as the fluid velocity required for maintaining a constant height bed of solids at the bottom of the conduit. Furthermore, different types of solids transport models exist: (1) empirical models, which were developed by fitting the model to the available experimental data (e.g., Rabinovich and Kalman, 2009); (2) mechanistic models, which were developed by balancing the forces and/or torques acting on the solid particle (e.g., Ramadan et al., 2003); and (3) semi-mechanistic models, which were developed using a combination of experimental data-fitting and physical laws (e.g., Oroskar and Turian, 1980). In deriving the models, different assumptions are made regarding the dominant mechanism for transporting the particle (i.e., dragging, rolling, or lifting), the shape of the particles (e.g., spherical), the initial location of the particle (at the bottom of the conduit, or on a bed of solids), the significant forces acting on the particle, and at times, the input variables to include in the model (typical input variables include the concentration, size, and density of the particle, the density and viscosity of the fluid, and the diameter and inclination angle of the pipe, although in some models, some of these independent variables are not included). When the solids transport models are developed, the ranges of experimental data used to develop and/or validate these models may differ from investigator to investigator. A more thorough review of these models can be found in Rabinovich and Kalman (2011), Shin (2013), and Soepyan et al. (2014).

It has been shown that the prediction of these models for the same input vector may differ several orders of magnitude (Soepyan et al., 2013). An example of this behavior for arbitrarily picked 30 input vectors can be seen in Fig. 1. Here, the velocity predictions of 68 different models are presented in a box–plot format. For each input vector, the central mark represents the median, the edges of the boxers are the 25th and 75th percentiles. Where exists, the whiskers represent the most extreme points that are not considered outliers, and the outliers are plotted as individual crosses. As this plot illustrates, the predictions of the models may span across four to five orders of magnitude for an input vector, and this wide spread in velocity predictions is typical. Therefore, these predictions are unreliable for effective design and operation of pipelines for oil and gas production.

The objective of this paper is to introduce a systematic approach that reduces model-prediction discrepancy for threshold-velocity estimation. The analysis is restricted to high particle concentration flows defined as above 100 ppm (volume/volume) in single phase carrier fluids – mainly liquid. Given an extensive experimental database of threshold velocities for different inputs, the approach partitions the data into similar characteristic clusters using data mining approaches. A model evaluation technique developed by our group (Soepyan et al., 2013) is used to determine the best solids transport model to predict the threshold velocity for each cluster. The last step of the approach correctly classifies a new design/operating condition (i.e., input vectors) to one of the existing clusters, and, uses the predetermined model for that cluster to estimate the threshold velocity for the input vector. A brief overview of different solid-fluid flow regimes and corresponding threshold velocity definitions are given in the next section. Section 3 introduces the compiled experimental database. Section 4 contains the details of the systematic approach, followed by the results in Section 5. Finally, conclusions are summarized.

2. Hydraulic transport modes at high particle concentration

Different solid particle patterns are observed for solid-fluid flow in a conduit depending on the concentration of the solids and the magnitude of the fluid velocity. According to Arevalo (2010), there are six types of flow regimes starting with the lowest flow velocity: (a) flow with a stationary bed, (b) flow with moving bed and dunes, (c) flow with moving dunes, (d) saltation (creeping, scouring) flow, (e) heterogeneous flow, and (f) homogeneous flow. Fig. 2 depicts these flow regimes. Flow with a stationary bed occurs at very low fluid velocities such that forces exerted on the particles by the fluid are not strong enough to entrain the particles up into the fluid (Fig. 2a). As the fluid velocity is increased, solid particles start to move in a dune fashion. These dunes are formed on top of the bed (Fig. 2b). At higher fluid velocities, the solid particles are transported as dunes (Fig. 2c). As fluid velocity increases more, “saltation flow” is reached. In this flow regime, the particles mainly start rolling and dragging at the bottom of the pipe (Fig. 2d). The fluid has enough energy to lift the particles from the sand bed, however, it cannot transport particles far away. A further increase in the fluid velocity will initiate the entrainment of solid particles in the fluid, and the flow regime defined as heterogeneous flow will be observed. At the heterogeneous flow stage, every solid particle is entrained and moving with the fluid. However, this flow regime is characterized by a non-uniform distribution of solids with a higher concentration of particles at the lower part of the conduit cross section (Fig. 2e). Finally, as the fluid velocity is increased further, the homogeneous flow, which has a uniform distribution of solids across the cross-section of the conduit, is reached (Fig. 2f).

Different threshold velocities can be defined as the necessary fluid velocities to transition between specific flow regimes. Commonly, six types of threshold velocities are encountered in the literature: (1) Equilibrium velocity is observed at the rate entrainment and deposition of solid particles are equal to each other, and when there is a static-height bed of solids in the conduit, (2) pick-up velocity is reached when the first particle lift-up from the bed is observed (the transition from flow regime a to b in Fig. 2), (3) scouring velocity is defined as the transition point between particles creeping and scouring to particles dragging and rolling constantly at the bottom of the pipe (from flow regime c to d in Fig. 2), (4) saltation velocity is the velocity at the settlement of the first entrained-particle to the bottom of the pipe, (5) critical velocity defines the necessary threshold velocity to transition from flow regime d to e in Fig. 2, and (6) dispersed velocity corresponds to the fluid velocity with the minimum head loss in the conduit, which can be characterized by the transition from flow regime d to e in Fig. 2.

3. Experimental database

The database contains 772 experimental data points collected from 12 different papers (Ambrose, 1952; Arevalo, 2010; Craven, 1952; Delavan, 2012; Goedde, 1978; Graf et al., 1970; Hayden and Stelson, 1978; Hill, 2011; Kenchington, 1976; Kokpinar and Gogus, 2001; Oroskar, 1979; Wicks, 1971). The experimental set-up and procedure used by each investigator can be found in