Powder Technology 292 (2016) 272–289

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Threshold velocity to initiate particle motion in horizontal and near-horizontal conduits

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A R T I C L E   I N F O

Article history:
Received 30 November 2015
Received in revised form 20 January 2016
Accepted 22 January 2016
Available online 27 January 2016

Keywords:
Solid particle transport
Force and torque balances
Threshold velocity prediction
Model uncertainty

A B S T R A C T

To initiate the motion of a solid particle in a conduit, the velocity of the carrier fluid needs to exceed the threshold velocity for particle transport. Several models have been developed that predict such velocity. However, none of these models provide information regarding the confidence of these predictions. In this paper, a new semi-mechanistic model is introduced using force balances on a particle in the horizontal and vertical directions, and torque balance on a particle. A unique contribution of this paper is the use of the bootstrap method to quantify the uncertainty of the model's prediction. This information is used to compute the envelope of the threshold velocity predictions to within a predetermined confidence level. We compared the performance of our semi-mechanistic model to existing models using statistical analysis and parity plots. The comparison suggests that our semi-mechanistic model is accurate, and is capable of explaining the variation in the experimental data. The threshold velocity envelopes suggested by our model cover the experimentally-observed values for 92%, 90%, and 93% of the experimental data for hydraulic transport from a bed of solids, pneumatic transport from a bed of solids, and pneumatic transport from the bottom of the conduit, respectively.

1. Introduction

The transport of solid particles in conduits is required in different applications, such as the transport of drug particles through breathing tubes for pharmaceutical applications [1], the transport of sand particles in pipelines in the oil and gas industries [2], and the removal of solid deposits in the tubes of heat exchangers [3]. There are many different forces acting on the particle immersed in a single-phase fluid, and the relative magnitudes of these forces determine the mechanism that initiates the movement of the particle. Past observations from various experimenters [3–8] suggest that the motion of solid particles may be initiated by dragging, rolling, or lifting.

To predict the minimum fluid velocity for initiating the motion of particles in conduits (i.e., the threshold velocity), different authors have used different assumptions regarding the dominant forces and mechanisms for solid particle transport (shown in Table S.1 of Supplementary Materials) to develop mechanistic and semi-mechanistic solids transport models [9]. Mechanistic models were derived from balancing the forces acting on the particle [6], while semi-mechanistic models were developed by balancing the forces and fine-tuning the parameters of the model using experimental data [10]. Initiating the motion of a solid particle from the bottom of the conduit at the incipient motion velocity [5], or from a bed of particles at the pick-up velocity [1] results in different solids transport mechanisms and dominant forces for particle transport [9]. The forces shown in Table S.1 include the drag force (F_D), the frictional force (F_F), the lift force (F_L), the normal force (F_N), the force due to the column of particles lying on top of the particle of interest (F_{part}), the plastic force (F_P), the force due to the turbulence of the fluid (F_T), the van der Waals attraction force (F_{VDW}), and the apparent weight of the particle in the fluid (F_W).

The Aussillous et al. [11], Doron et al. [12], Ling [13], Ramadan et al. [6], Rampall and Leighton [14], and Wu and Chou [15] models were developed to predict the threshold liquid velocity for a particle initially at rest on a bed of solids. Aussillous et al. [11] observed that for the hydraulic conveying of particles from a bed of solids, the particles are transported by fluid shearing, where the particles roll and slide (i.e., drag) over the surface of the bed. Furthermore, Aussillous et al. [11] noted that there must be a large turbulence in the flow in order for the lift force to be significant. Thus, in developing their model for a spherical particle, Aussillous et al. [11] only considered motion in the

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http://dx.doi.org/10.1016/j.powtec.2016.01.031
0032-5910/

horizontal direction, where the normal force resulting from the contact between two particles is used to relate the drag force to the apparent weight of the particle.

The remaining models, which also assume the particle to be spherical, do not consider the drag mechanism, because these models were developed using torque balance for the case of particle roll, and/or vertical force balance for the case of particle lift. The only exception is the Rampall and Leighton [14] model, which was developed by considering different phenomena, such as viscous re-suspension, near-wall turbulence, and turbulent re-suspension. Doron et al. [12] computed the minimum pick-up velocity by balancing the driving and opposing torques acting on the solid particle in the lowest stratum of the moving bed layer of the fluid. Similarly, Wu and Chou [15] assumed that in order to roll the particle, the encouraging torque (due to the drag force and the lift force) must exceed the resisting torque (due to the weight of the particle). To lift the particle, Wu and Chou [15] balanced the dynamic lift force acting on the particle with the particle's weight. Similar to the Doron et al. [12], Ramadan et al. [6], and Wu and Chou [15] models, Ling [13] incorporated the drag force in his model. However, the Ling [13] model considers two types of lift force (shear lift and the lift due to the centrifugal force acting on the particle). Both Doron et al. [12] and Ramadan et al. [6] developed their models assuming that the pipe may have an inclination. Ramadan et al. [6] assumed that fluid flows over a stationary bed of solid particles of uniform thickness and found that the threshold velocity for particle motion is influenced by the inclination angle of the conduit.

Fig. S.1 of Supplementary Materials compares the threshold velocity predictions of the above models against experimental data for the hydraulic conveying of a solid particle initially at rest on a bed of solids [6,16–24]. The experimental data can be found in Tables S.2 to S.4 of Supplementary Materials. The Wu and Chou [15] model tends to underestimate the experimentally-observed threshold velocity, where most of the threshold velocity predictions of the model fall below -50% of the experimentally-observed values. Meanwhile, the remaining models [6,11–14] tend to overestimate the experimentally-observed threshold velocity for the experimental data from Agudo and Wierschem [23], where the experiments were conducted in a stirred vessel with highly viscous fluids (with viscosities of $\sim 10^{-2}$ and $\sim 10^{-1}$ Pa $\cdot$ s), and flow depth in the order of 10^{-4} and 10^{-3} m. As for the remaining experimental data points, the Aussillous et al. [11], Doron et al. [12], and Ling [13] models are biased towards underestimating the experimentally-observed threshold velocity; the Rampall and Leighton [14] model has a bias towards overestimating the experimentally-observed threshold velocity; while the Ramadan et al. [6] model does not show any bias.

For the pneumatic transport of a solid particle from a bed of solids, Cabrejos [25] extended his model for the pneumatic transport of a solid particle from the bottom of the conduit by multiplying the incipient motion velocity prediction of this model with correction factors that incorporate the dimensionless Archimedes number. The model developed to predict the incipient motion velocity is denoted “Cabrejos [25] single particle model,” while the model developed to predict the pick-up velocity is denoted “Cabrejos [25] multiple particle model”. In his work, Cabrejos [25] mainly focused on the effects of the particle size on the threshold velocity. His main findings suggest that the mean diameter of the particle, the coefficient of static friction between the particle and the pipe wall, and the particle shape are important factors that affect the magnitude of the threshold velocity. For the case of particle drag, Cabrejos [25] balanced the drag force with the friction force acting on the particle, while for the case of particle lift, the upward forces (i.e., the lift force and the buoyancy force) are balanced with the downward forces (i.e., the gravity force and the van der Waals attraction force). Hayden et al. [1] used the same force balance as that of Cabrejos [25] to develop their model for particle lift.

The comparison of the threshold velocity predictions of these models (Fig. S.2 of Supplementary Materials) against experimental observations [7,8,25,26] suggests that the Cabrejos [25] multiple particle model tends to overestimate the experimentally-observed threshold velocity, where most of the predictions exceed $+50\%$ of the experimentally-observed values. On the other hand, the Hayden et al. [1] model shows a near-horizontal trend in its parity plot, where the threshold velocity predictions of the model remain fairly constant even though the values of the experimental threshold velocity increase. This behavior suggests that this model may be missing at least one important variable.

The Cabrejos [25] single particle, Han and Hunt [27], Ibrahim et al. [28], Rabinovich and Kalman [29], and Stevenson et al. [3] models were developed to predict the threshold fluid velocity for transporting the particle from the bottom of the conduit. Han and Hunt [27] balanced the lift force produced by the velocity gradient of the liquid and the viscous force with the gravity force acting on the particle; while Stevenson et al. [3] developed a model that predicts the threshold velocity required to drag a hemispherical particle initially at rest at the bottom of the conduit. Stevenson et al. [3] assumed that the particle is submerged in the viscous sublayer of the fluid and that the drag mechanism is dominant because of the hemispherical shape of the particle, and developed their model for both the hydraulic and the pneumatic conveying of the particle. On the other hand, Ibrahim et al. [28] and Rabinovich and Kalman [29] considered the possibility that the solid particle may initiate its motion by dragging, lifting, or rolling. Ibrahim et al. [28] developed their model for the case of the detachment of micro-particles from surfaces exposed to turbulent air flow. The threshold velocity is found to be dependent on the particle's size, shape, and surface energy of adhesion. Similar to Stevenson et al. [3], Rabinovich and Kalman [29] developed their model for both the hydraulic and the pneumatic transport of a solid particle. Here, force analysis was done explicitly for coarse non-spherical particles, coarse spherical particles, fine particles in air, and fine particles in water.

The threshold velocity predictions of the above models are compared against experimental observations (Fig. S.3 of Supplementary Materials) for the case of the pneumatic conveying of solids from the bottom of the conduit [3–5,8,25,30]. The Han and Hunt [27] model was not included in the comparison because this model was developed for the hydraulic conveying of solids from the bottom of the conduit. The above models [3,25,29] have a bias towards overestimating the experimental threshold velocity, except for the Ibrahim et al. [28] model. Here, the Ibrahim et al. [28] model tends to produce errors that are less than -50% for the experimental data points where the particle diameter is in the order of 10^{-3} m.

The above comparisons suggest that some of the available mechanistic and semi-mechanistic models for predicting the threshold velocity do not adequately capture the effects of all of the forces for solid particle transport. Most importantly, the uncertainty of the threshold velocity predictions of existing mechanistic and semi-mechanistic models is not readily available. Such information is essential for quantifying the confidence that the threshold velocity prediction is sufficient for transporting the solid particles in the conduit, or for estimating the probability of transport at a given fluid velocity.

In this paper, we present a semi-mechanistic model for calculating the threshold velocity by quantifying the different forces acting on a particle initially at rest. Our model takes into account the initial location of the solid particle, whether sitting on the pipe wall (incipient motion velocity) or on a bed of particles (pick-up velocity). The model was developed by balancing the forces in the horizontal and vertical directions, and the torque, to quantify the threshold velocities for the cases of the initiation of particle motion by drag, lift, and roll, respectively. For estimating the horizontal drag force, we developed correlations that relate the drag coefficient (for the cases of the initiation of particle motion by dragging and rolling) to the particle Reynolds number (described in Section 4). The bootstrap technique (described in Section 5) is used to quantify the uncertainties of the model's predictions. It is here that our model development approach deviates from previous ones. Having information regarding the uncertainties of the threshold velocity prediction of the