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Particles' degradation and dynamics in conveying systems

Avi Uzi [a,*], Avi Levy [a]

[a] Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O. Box 653, 84105 Beersheba, Israel

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ABSTRACT

The attrition process of particles in conveying systems is a common problem in many industrial applications. The current study adopts a new approach to modeling particle breakage by implementing one-dimensional breakage algorithm (ODBA) in a one-dimensional flow model (Uzi et al., 2016). This method is used for the first time in two-way coupling, i.e. when the breakage affects the flow dynamics and vice versa. The one-dimensional flow model uses conventional balances of mass, momentum and energy. Moreover, the ODBA exploits empirical correlations for particle characteristics (i.e. breakage, equivalence and fatigue functions), and dynamic behavior (i.e. impact velocity and frequency) obtained from a coupled 3D CFD and Discrete Element Method (DEM) simulations. Both the dynamics of the particles and the attrition of the particles were validated using the proposed approach. A dilute pneumatic conveying system was considered, which comprises of 1 in. pipe and 5 straight sections and 4 bends (R/D = 1) with a total length of 14.5 m. CFD-DEM results served as the basis for the velocity validation, satisfying a good agreement along the conveying line. In this system, the attrition of Potash particles was simulated and compared with the experimental measurements of Kalman et al. (2004), showing an excellent agreement. This comparison consists of inlet gas superficial velocity of 40 m/s and is comprised of ten conveying cycles in order to emphasize the fatigue phenomena. The investigated case was also analyzed to provide the dynamic parameters of the two-phase flow with regard to the coupling with the breakage algorithm. It was well established that the flow parameters are sensitive to particle size. In the pressure variation, it was prominent that larger particles resolve a larger pressure drop, while the differences between the cycles in the velocity were more extensive. These differences were caused by the changes in particle size distribution and actualized due to the two-way coupling approach.

1. Introduction

Particle attrition during pipeline conveying is a major problem in many industrial applications. When solid particles are conveyed through pipelines, they are subjected to collisions with other particles and with the pipe wall, which may cause particle degradation, mainly in high conveying velocities when the flow is fully-suspended. Many experimental studies focused on the attrition phenomena in pneumatic conveying [1–11]. The aim of these studies was to describe the trend of the changes in size distribution. This may be described in terms of several characteristics such as: particle strength, initial particle size, fluid superficial velocity, pipe diameter, particle volume fraction, and solid loading ratio (the ratio between solid to fluid mass flux). The common way to examine attrition in these experiments is to compare the inlet and outlet size distribution at specific conditions. Obviously, it would be very beneficial if one could correlate the results with the experimental conditions to generate a prediction for designing purposes. In practice, however, it appears to be highly complex to link those results with the governing parameters in order to receive a general correlation. The difficulties arise from the multitude of parameters and the complications in describing the strength characteristics of the particles.

One possibility for overcoming this issue is the application of computational methods for predicting the attrition in a particular case of interest. Unfortunately, only several researchers (e.g. [12–18]) have implemented breakage in their simulations, thus it is currently accessible only to a limited number of applications.

When simulating a degradation process, the model must account for the particles' dynamics and exploit the dynamics data to determine the particle breakage. One applicable approach that was developed for this purpose is a combined Computational Fluid Dynamics (CFD)-Discrete Element Method (DEM) [15,18–20]. In this approach, the fluid is treated as an Eulerian phase and the particles are considered discrete entities. A number of techniques were implemented into the CFD-DEM approach in order to calculate particle breakage [19], however only the 'fragment spawning' model [20] has been implemented to simulate a pneumatic conveying system [18]. The fragment spawning model integrates

Abbreviations: CFD, computational fluid dynamics; DEM, discrete element method; ODBA, one-dimensional breakage algorithm.

* Corresponding author.
E-mail address: uziav@post.bgu.ac.il (A. Uzi).

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empirical comminution functions, developed by [21], into the CFD-DEM code in order to calculate particle breakage. The comminution functions includes: 1) a breakage function that describes the amount and sizes of the sibling particles after the breakage [22], 2) a strength distribution function, which defines the maximum compression force that may be applied on a particle before it breaks [23], 3) an equivalent function that relates the impact velocity to the compression force [24] and 4) a fatigue function that is applied in order to calculate the particle's modified strength upon collision [25]. The CFD-DEM solver, combined with these comminution functions, enables to capture every collision event and to determine whether, upon collision, the particle will be broken or weakened. Therefore, with this tool it is possible to simulate particle degradation in any process. It should be noted that as of yet, the above comminution functions were published only for a limited number of materials. Thus, further development is required in order to enable the applicability of the fragment spawning model to other materials. In addition, the major drawback of this method is the immense computational cost, as the number of particles is increased and their size substantially decreased during the breakage process.

An alternative approach is modeling the flow with a simplified macroscopic model, i.e. a zero-dimension or one-dimensional two-phase flow model, and applying another model to account for the breakage process. Such an approach is beneficial, since it is much faster than CFD-DEM, yet it is less accurate than the DEM approach.

Chapelle's model is one example for such an implementation on a large-scale pneumatic conveying line [12]. In this degradation model, a breakage matrix is derived from single impact tests and then implemented on every impact event in the simulation. The particles impact velocities in this model are evaluated by a zero-dimensional flow model, so that all particles are traveling with the same velocity (and therefore colliding with the same velocity). It should be noted that when using a zero-dimension flow model, the two-phase flow dynamics ignore the effects caused by particle size reduction along the pipeline. In addition, in Chapelle's model, collisions are assumed to occur perpendicular to the wall and only in bends (without accounting for particle-particle interactions), the fatigue phenomenon is neglected (although it has been previously demonstrated that fatigue has significant influence on particle breakage [9,25,26]), and the influence of size distribution changes on the fluid dynamics are ignored.

The objective of the present study is to take into account all of the above-mentioned effects for simulating breakage in pneumatic conveying. Our model uses a conventional one-dimensional two-phase flow approach for calculating the two-phase flow dynamics, as well as a one-dimensional breakage algorithm (ODBA) to account for breakage.

The ODBA concept was first introduced in Uzi et al. [27], and it includes two components: 1) a tool that depicts collisions dynamics, i.e. frequency and velocity of impacts distributions, and 2) empirical comminution functions which characterize the particle's response to collisions (the four functions detailed above). The ODBA model replaces the heavy CFD-DEM simulation, which serves only as a machine function. Thus, instead of employing a 3D two-phase flow to depict collisions, the ODBA uses two statistical functions: collision frequency and velocity distribution. These functions were derived from CFD-DEM simulations using potash particles (with corresponding properties: density, Young modulus, Poisson ratio, restitution coefficient, friction coefficients) within the DEM, in which the particles were treated as spheres with sphericity of 0.8 for the drag model. In order to produce the statistical functions, every collision between the particles and between the particles and the walls was recorded for subsequent analysis. Thus, all of the complicated effects of the particles' flow pattern within the 3D domain are expressed statistically through the machine functions.

For the purpose of simulating attrition in pneumatic conveying, the ODBA approach has different advantages over other existing models. This model allows to emphasize the fatigue phenomenon, accounts for particle-particle interactions as well as particle-wall interactions, both in straight pipes and in bends, and it is much faster than the full CFD-DEM breakage simulation. The ODBA was recently implemented in one-way coupling for dilute-phase pneumatic conveying [27] and was validated in Kalman et al.'s [9] experimental results. The validation showed good agreement with the attrition results measured after several conveying cycles, even though the attrition process (i.e. particle size reduction) was assumed not to affect the dynamics of the two-phase flow. Therefore, in the one-way coupling approach the effects of breakage on the particle and gas dynamics were not investigated [27].

In the current study, we aim to address this gap by modifying the coupling method of the ODBA with the one-dimensional flow model, from one-way coupling to two-way coupling. This coupling between the two-phase flow model and the ODBA allows examining attrition as well as the flow dynamics of both the gas and the particles over a long range of conveying pipelines, in which particle degradation plays a significant role, in a short computation time. The novelty of this implementation is its emphasis on the effects of particle breakage on the flow field and vice versa, which, despite their immense importance, are rarely analyzed or considered in the literature.

2. Model description

Particle attrition is strongly affected by the particles' properties (i.e. strength, density, size etc.), carrier fluid properties, fluid flow dynamics and the conveying line's geometry. The two-phase flow model and the ODBA together function as an adaptive tool that can be modified easily to account for these effects along with attrition assessment. The one-dimensional two-phase flow model and the ODBA are used in the present study to predict attrition and to account for the effects of particle attrition over fluid dynamics. It is important to mention that when the fluid dynamics calculations are influenced by attrition, this directly affects the breakage calculations themselves, and therefore the influence is mutual.

The ODBA utilizes the comminution functions [21–24] as the particle characteristic tool, and the machine functions as the collision characteristic tool, i.e. how often the particle would collide (frequency distribution function) and what its impact velocity (velocity distribution function) would be. In the present study, these two functions are adopted [27]. These functions were developed by applying 3D CFD-DEM simulations. The simulation captures every collision event throughout the domain and the collision data is stored for subsequent statistical analysis which provides the machine functions.

2.1. One-dimensional two phase flow model

The pneumatic one-dimensional flow model is described in detail in our previous publication [27], but a brief outline is given here for the sake of completeness.

In dilute phase conveying systems, when the particle phase is fully suspended, the particles can be modeled by a homogenous suspension. In the one-dimensional flow model, the steady-state balance equations of mass, momentum and energy are solved to predict the two-phase flow dynamics. According to the previous study [27], the one-dimensional flow model assumes that the diameter of the particle phase is a scalar that is defined at the inlet as the median size (d_{50}) of the particles, and it remains constant along the conveying line. The major improvement of the model in the current study is that the flow modeling takes into account the changes that occur to the median particle diameter due to particles' degradation along the conveying line, corresponding to the results from the ODBA.

2.2. Pneumatic one-dimensional breakage algorithm

The breakage model combines statistics from CFD-DEM simulations and empirical particle characterization. The ODBA is coupled with two-phase flow dynamics (supplied by the one-dimensional two-phase flow model) in a two-way coupling. In the two-phase flow model, the