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Coupled gas-particulate discharge from a bucket elevator

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ABSTRACT

The vertical conveying of bulk materials is often performed using bucket elevators. Such devices use conveyor belts to drag a series of buckets in a circuit, up, around and then down within an enclosure. They are typically used for upward transport of fine granular materials. The speed at which these buckets travel can displace a large volume of air. Interaction between this air and the bucket contents can modify the discharge dynamics of the granular load. A coupled gas-particulate numerical model is presented using Finite Differences to solve for the gas flow with an Immersed Boundary Method (IBM) to represent the complex bucket and enclosure geometry in the model. The Discrete Element Method (DEM) is used for particulate flow. The combined method is used to investigate the effect of gas flow on particulate behavior, particularly at the time of discharge from the buckets. The bucket elevator design used is based on an existing installation with known operational issues. The presence of gas flow is shown to alter the preferential ejection of particles from the bucket, influence the shape of the trajectory of the ejected particle stream, and reduce the efficiency of particles exiting the elevator by 10–14%. These effects are also shown to be strongly size dependent with finer particles being much more susceptible to drag forces from the air flow. The retention of material inside the machine was found to consist of roughly 50% of material centrifugally ejected from near the bucket tip and roughly 70% of material located closer to the conveyor belt side of the bucket that spills off the splitter during the final stage of emptying and falls back down to the boot.

1. Introduction

Bulk materials handling for large silos or multi-floored industrial operations often require continuous transport of granular material across large vertical distances. The most commonly used mechanical conveying device for such applications is a bucket elevator conveyor. The simple construction and compact footprint of these devices, and their broad scalability make them a popular component of a bulk materials handling assembly. They are either of the gravitational discharge type where particles fall out under gravity or the centrifuging discharge type where particles are ejected from the periphery of the bucket under centrifugal force as the bucket motion changes from linear to circular around the head pulley. In the case of a centrifuging discharge system, this typically consists of a series of widely spaced buckets bolted to a conveyor belt which follows a closed vertical (or heavily inclined) path with the entire system typically housed inside a long enclosure [1]. The buckets follow the motion of the conveyor and continuously pass through the bottom of the enclosure ("boot") and collect material that is either supplied on the upward leg or is scooped up from the buildup of material inside the boot originating from spillage at the head pulley. The intended mode of emptying for such a system is for complete centrifugal discharge of bucket contents during passage around the head pulley. However, the operating conditions or design of a particular device may lead to poor emptying efficiency which results in significant amounts of material remaining inside the bucket as it decelerates at the end of the head pulley. The final stage of emptying of bucket contents is then dominated by gravity so that the total emptying process is a combination of centrifugal and gravity discharge.

However many maintenance issues are associated with these devices. This is generally a consequence of poor belt tracking or tension leading to early bucket wear [2]; or poor feed/discharge efficiency which can lead to spillage, reduced throughput and material retention inside the main enclosure. The dominant wear mechanism in bucket elevators is abrasion due to sliding of the bulk material over bucket, enclosure, belt and chute surfaces. To manage this, buckets are commonly made of industrial plastics or wear-resistant pressed steels, and chutes are often lined with wear-resistant materials. Airborne particles in a strong gas flow also produce an abrasive environment for the enclosure and chute walls. However, coarser particulates tend to be the largest cause of machine wear both because of their larger momentum but also because they are able to move independently of the gas and collide with surfaces. For conveyors which are used for transporting multiple materials, a recycling load inside the enclosure can lead to cross-contamination between products [3] or even promote insect infestation inside organic materials accumulating in the boot [4]. The recycling load

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can leave fine material on equipment surfaces which is then carried over into the next batch of material to be conveyed. For very light materials such as flour, cement or fly ash, poor feed and discharge efficiency can often arise from turbulent air flow inside the buckets and enclosure interacting with these materials. The buckets commonly occupy much of the space between the conveyor and the confining enclosure with only modest clearances around the bucket so that the buckets entrain and displace large volumes of air. This air movement often enters the buckets, blowing off large quantities of fine material which can settle into other buckets below or accumulate inside the boot. Inadequate venting when conveying combustible materials (such as sugar) can cause significant risk of explosion or fire [5] due to the continual suspension of fine reactive dust inside the main enclosure combined with frictional heat due to belt slip or high bearing temperatures. Differences in air pressure inside and outside the bucket can also result in incomplete filling or discharge. These pressures are sometimes moderated by the inclusion of venting holes in the bucket floors. The air flow inside the chute also applies drag forces to the stream of discharging particles. This can modify the particle trajectories and therefore influence which particles are directed into the discharge chute and which ones fall back into the boot. Since the influence of air drag is strongly particle size dependent this creates opportunities for significant and undesirable segregation effects and product composition variations.

Computational models for predicting the behavior of large-scale granular assemblies using particle-based methods such as Discrete Element Method (DEM) make it possible to assess the suitability of equipment design choices and to evaluate operational what-if scenarios prior to the construction of a full plant. They are increasingly being used to solve process problems, guide the redesign of equipment, and improve operational efficiency for many industries that involve processing, transport and handling of bulk materials. Perhaps surprisingly, up until now very few granular flow models of bucket elevators exist in the literature. McBride et al. [6] developed a 3D DEM model of the centrifugal discharge dynamics of the upper section of a bucket elevator. This included the effect of dynamic belt deformation due to bucket acceleration around the head pulley and the effect of this on material discharge but ignored the air flow component. Boac et al. [7] investigated the lower section of a bucket elevator using 3D and quasi-2D DEM models, also ignoring the gas flow, to understand the blending of soybeans when fed into the boot and scooped up by buckets. Pérez-Aparicio et al. [8] have developed 2D models of bucket discharge for a variety of bucket shapes and bulk materials using discontinuous deformation analysis. None of these studies included the effect of the gas flow on particulate behavior which is a significant limitation. Alternative methods of bulk transport such as an OLDS elevator [9], screw conveyors [10–12] and pneumatic conveying [13,14] have also been modelled with DEM.

Understanding the dynamic behavior of gas-particulate systems is of fundamental interest to a broad range of process industries. The complexity of particle-particle collisions and their interactions with non-steady gas flow do not permit solution via analytical methods and are not sufficiently well represented by numerical models which only model the gas flow. Comprehensive reviews of CFD simulation of gas-particulate flows for industrial applications can be found in [15,16]. Computational Fluid Dynamics (CFD) models using an Eulerian-Eulerian approach represent both the gas and particulate solids as continuum phases which interact. These models are computationally less demanding than methods that resolve the granular nature of the solids and the detailed nature of their collisional interactions. However such models are unable to predict dynamic changes to the particle microstructure and porosities that the gas field interacts with. They also ignore details of gas drag at the particle scale such as dependence on particle shape and orientation. Alternatively coupled Eulerian-Lagrangian methods have been formulated to more accurately model the particulate phase as discrete particles using DEM. This type of method was first proposed by Tsuji et al. [17] as a two-dimensional model which used circular particles and a coupled gas flow to model pneumatic conveying. This type of model has most typically been used for studying fluidized beds [18–23]. A detailed review of such models is given in [24]. The coupled DEM-CFD approach has been used for 3D simulation of spherical particles to study flow regimes in spouted fluidized beds [25]. Guo et al. [26] used 2D simulations to look at the effect of a moving object inside a fluidized bed using the Immersed Boundary Method (IBM). All of these studies assumed that the particles were spherical whereas real materials can have highly non-spherical particle shapes. Hilton et al. [27] introduced modelling of blocky and high aspect DEM particles with a Finite-Difference (FD) gas flow. This was shown to have significant impacts on the gas transport behavior for pneumatic conveying [13] and gas injection into granular beds [28]. Zhou et al. [29] have considered the effect of ellipsoidal particles and also identified shape-dependent effects on gas transport through a fluidized bed.

The aim of this study is to investigate the impact of air flow on the behavior of realistic shaped particles and how this affects overall discharge efficiency of the machine during the operation of a centrifugal discharge bucket elevator. The particular bucket elevator design has been studied previously using DEM [6] but ignored the air flow. This configuration is based on an existing installation which has identified operational/design flaws, such as having a small air gap between bucket tip and the walls of the enclosure which leads to poor transport and the greater wear on equipment surfaces. Here, the intention is to analyze the operation of a realistic bucket elevator assembly to demonstrate the general importance of including the air flow in the model and to show how air flow-related problems can be identified rather than to optimize the design and operation of this machine configuration. A coupled DEM-CFD model of the discharge of a granular load of spherical beads from the buckets is used to understand how particle size influences the material retention inside the bucket elevator and enclosure. The degree to which preferential discharge or retention of solids depends on the initial location in the bucket is also considered.

2. Numerical method for 2-way coupled DEM-FD

DEM is used to model the granular material in the bucket while coupled gas flow is solved using the Finite Difference (FD) method.

2.1. Discrete Element Method (DEM)

Numerical models for the granular flow of bulk materials are possible using DEM which predicts the motion and interactions of individual grains. For each computation timestep, all resolved particles are tracked and the forces between particles and between particles and boundaries are calculated. A contact force model determines the outcome of each collision. In this work a linear spring-dashpot contact model is used. The spring force represents the elastic loading of particles and a dashpot provides the energy lost in inelastic collisions. The particles used in this model will be spherical. Mesh representations for bucket, belt and chute geometry are provided to the DEM solver for use in contact detection and prediction of interactions. Particle-particle and particle-boundary collisions are modelled by calculating the particle overlap between particles and between particles and each mesh element. The specific DEM software used is the one described in [30,31] and has been applied to a broad range of mineral processing [32,33] and bulk materials handling [10,13] applications.

2.2. Finite-difference (FD) gas model

Governing equations for gas flow through a porous bed are used for modelling the gas system, as given by [22]. The gas velocity is defined using two variables: the interstitial velocity of the gas between the particles, $\mathbf{u}$, and the averaged bulk velocity of the gas, called the superficial velocity, $\mathbf{u}'$. The gas density is assumed constant, so the gas is incompressible and velocities can be linked by the expression $\mathbf{u}' = \varepsilon\mathbf{u}$ and ε