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Segregation phenomena in gravity separators: A combined numerical and experimental study

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ABSTRACT

In this paper we formulate a computational framework for characterizing and optimizing the performance of a destoner, an example of a density-based separation technique. The numerical framework combines Computational Fluid Dynamics (CFD) simulations with a Discrete Element Method (DEM), implemented in an open-source computation package (OpenFOAM). This framework is validated first by comparing the simulations with experiments for a standardized test case and further with our experimental study of a pilot-scale destoner. We evaluate the combined effects of process conditions, such as separator deck inclination, vibration speed and fluidization velocities on destoner performance. Our simulations show how the heavy product fraction in the discards stream increases over time with a corresponding accumulation of the 'valuable' light product at the base of the deck, indicating segregation between the stones (heavy product) and the grains (light product). We also find that these separation profiles are highly sensitive to changes in deck surface air velocities, with the gradual development of segregation zones at velocities close to the minimum fluidization velocity of the heavier component. Optimal separation is seen at a deck inclination of 4° and a fluidization velocity of between 1.75 and 2 *m/s*. Our simulation results also agree well with the experimental findings indicating the usability of the proposed framework for the design and optimization of gravity separators.

1. Introduction

At present, purity and quality are identified as two criteria of great relevance for food production. In the same time, maintenance of high standards of quality in production is a challenge that has always been pushing forward the existing technologies. Historically 'winnowing', a process that involves the tossing of harvested feed in natural streams of air, has been employed to remove chaff from good product. This rudimentary cleaning practice utilizes the ambient wind to blow away the lighter chaff, while the heavier grains fall back down for recovery. Over the years, this ancient practice has been refined and developed into modern machinery processing at large volumes which can effortlessly clean harvested crops. The primary aim of such processing is to obtain clean, pure seeds of high quality (yield) which can be stored and easily handled during succeeding processes, such as pretreatment, transport and sowing. The ideally cleaned seed lot consists of all viable seeds of the target species, and is free from any other matter. This paper elaborates on one such downstream cleaning operation, i.e. removal of stones achieved by using a destoner, operating under the fundamental principle of separation of similarly sized entities and based on specific gravity or density. We propose here an in-silico process optimization framework for such a device. In the same time, the framework represents a contribution to fundamental understanding of the physics of gravity separation.

The operation of a destoner (Fig. 1) is principally driven by fluidizing air (released from the surface of the deck) that sorts the grains based on their specific density, with grains rising or falling by their relative weight with respect to air. A mixed feed of harvested product, consisting of auxiliary impurities such as stones and bran, is introduced onto the deck of a destoner for cleaning. An inclined oscillating deck transports the heavier contaminant (e.g. stones) towards the higher end, while the lighter grain is collected at the base. The segregation patterns on the deck of a destoner are primarily controlled by three main factors: fluidizing air, reciprocation frequency of the deck and deck tilt. Other extrinsic (i.e. fixed) factors, such as stroke length for the throwing

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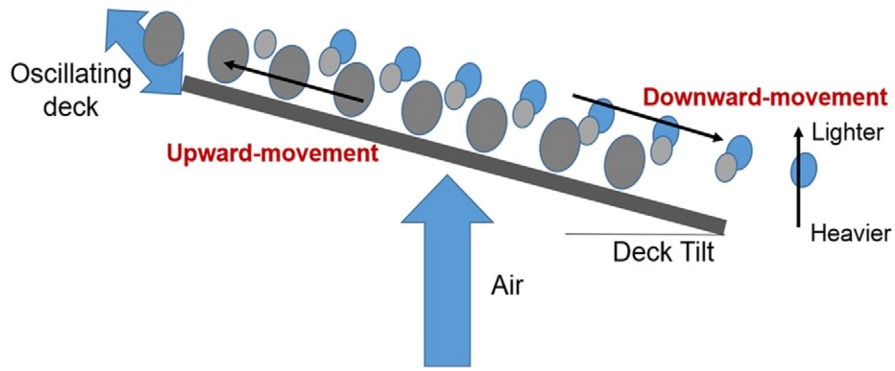

Fig. 1. Principle of gravity separation: The grains are sorted based on their specific density with grains rising or falling by their relative weight to air. The black arrows indicate the corresponding movement of the lighter (blue colored) and heavier (grey colored) material.

action, as well as the deck surface friction, also affect the behavior of the grains on the deck. The performance of the gravity separators is mostly reliant on these intrinsic factors.

The scope of the current work is derived from the relatively limited amount of work (empirical or computational) on other closely related applications such as shaking separation of rice and paddy. Additionally, staying abreast with recent advances in computational tools, the current work also aims to utilize some of the underlying principles of these reported studies. An empirical basis of granular segregation phenomena can be obtained by examining these related studies on shaking separation of rice. The mechanism of movement of paddy and rice in opposite directions on an oscillating tray separator was first proposed by Das [1]. This mechanism attributed separation to the existence of differences in coefficients of friction between paddy and the deck, rice and the deck and paddy and rice respectively. A similar surface contact-dominated mechanism could also be applicable to gravity separators. The deck of a destoner has high surface friction to ensure that there is sufficient traction between the particles and the surface in order to prevent contacting grains from easily rolling down towards the lower end.

In addition to these efforts, several numerical studies have been carried out to model transport phenomena (such as heat flow and fluid flow) within food and grain downstream processing applications as reported in literature [2–4]. Numerical simulations can provide dynamic information, such as trajectories of individual grains and forces acting on them. Similar information is, on the other hand, difficult to obtain by experiments [5]. These studies capture the general flow behavior of the ambient fluid, consequently aiding in the design and development of units regularly utilized in food and grain processing, such as refrigerators, mixers and spray dryers. In order to investigate the granular flow behavior, a purely continuum-based description of a system would not suffice. A Discrete Element Method (DEM) framework [6], which is based on tracking individual particles in a domain of interest, has been a popular choice for several research groups interested in studying discrete granular interactions such as collisions and clumping. The reported applications of DEM to food and grain processing applications are limited to fundamental case studies (dealing with the behavior of a few hundred grains) including numerical studies on the separation process of soybeans and mustard seeds by a vibrating screen [7] and simulation of the shaking separation of paddy and brown rice [8]. Comparison of the simulations with experiments in the latter work showed good agreement in respect to the wave-like behavior of the grain assembly and the macroscopic separation behavior.

The aforementioned DEM-based studies on food and grain downstream processing units do not include effects of the ambient fluid on granular interactions (i.e. there is no interstitial fluid present). Hence, these descriptions alone cannot satisfactorily describe systems where the interstitial fluid markedly affects the particulate flow, as is the case in the context of this work. A coupled approach [6], where the particle trajectories are evaluated together with the resolution of the fluid flow field, is therefore needed to describe such systems. This approach has been successfully adopted to describe fluidized beds, downers and other units routinely used in chemical processing [9–12]. The current work aims to extend the application of such frameworks to describe gravity separators.

Note that it is not trivial to characterize both experimental and numerical studies of granular flow behavior on the deck of a destoner. The correlations among the following process operating conditions are to be understood:

- Deck side tilt: The difference in elevation between the high side of the deck (waste product) and the low side of the deck (good product). The efficiency of separation between the lighter grains and heavier stones is determined in part by the extent of the side tilt. Increasing the tilt causes a material to shift towards the low side of the deck with the best separations obtained close to maximum steepness.
- Deck eccentric speed: The vibration of the deck is achieved using an eccentric which would rotate, off-centre to generate a throwing action (transverse motion at an angle). This action of the deck converts the vertical material stratification zones generated by the fluidizing air into horizontal sections along the deck surface.
- Deck fluidizing conditions: The aeration system in a gravity sorter, consisting of an air intake/filter, blowers and a distribution system, is principally responsible for separating the heavy material from the light one. Hence, it is essential to have a fairly uniform air distribution across the deck.

We formulate in this paper a coupled CFD-DEM framework in order to investigate relevant system properties of a destoner as a function of the operating conditions (in particular, the deck tilt and fluidization conditions). The developed framework will be used for optimization of existing devices and design of the new ones. We validate our results with experiments on a pilot unit using a Point Grey USB 3.0 Camera (Flea3) and formulate a statistical procedure in order to provide comprehensive information on the granular flow behavior on the surface of the pilot unit.

2. Simulation method

We describe in this section the coupled CFD-DEM framework and the corresponding numerical setup used in the current work. In addition, we present here a description of the metrics adopted to adjudge performance of the destoner studied in this work.