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Empirical study on the effects of screen inclination and feed loading on size classification of solids by gravity

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ABSTRACT

This study explored the insights into the theory of dry solids classification, in particular the classical dynamics aspects related to the mass loading of particles, deck inclination of the screen, and resulting measures of flowability. Prototype screening equipment was fabricated and experiments were carried out with ideal rounded mono-shaped glass beads. The overall performance of the prototype was assessed in relation to two screen design variables, the tilt angle of inclination and the mass throughput of the feed, which affects particles flow. Mathematical models relating to the classification process were developed, simulated and compared to the results obtained from the experiments. Important parameter ranges within which equipment may be operated with minimal malfunctioning were approximated from the models. Screen loading, bulk flow velocity, and screen inclination angles determine flowability of powders and particles in gravity classification; these parameters were used in this study to assess how well the particles flowed over the screens. A close correlation was found between theory, simulation models and the experimental results, which facilitated development of empirical models that may be used to predict and estimate the classification rates, efficiencies and flowability for such systems. Dense screen loading improved the classification rates, but hampered flowability, and consequently the efficiency. Increase in deck inclinations improved flowability and efficiency, but only to a certain optimum point after which it led to excessive overflow.

1. Introduction

Mineral ores and their gangue are usually sorted into grades of various sizes to maximize recovery of the primary product during concentration. Gravity classification which has been in use for many years is a very important process mostly in mining and other related industries. To realize the full potential of a production plant, cost effective strategies such as gravity classification must be exhausted before resorting to more energy intensive options (which may not necessarily be more efficient). Thus, detail understanding of the process is necessary. This research is built upon the models developed in an earlier work in which it was proposed that the rate of particles classification is proportional to the rate of change in momentum (P), and the screen area, and inversely proportional to the particles diameters. Successful development of the approach would enable gravity-based systems e.g. deck screens, to be applied not only in the minerals industry but across process industry as a whole (Rotich et al., 2013). Knowledge of process flow conditions together with information about the flow properties of materials over different equipment surfaces will enable process engineers to optimize material handling operations by utilizing approximate empirical models for instance, to predict material flows. Possible applications also exist in other areas such as, coal beneficiation or biomass classification during pre/post combustion, municipal solid waste management, food cereals processing, pharmaceutical, agricultural products and farm inputs, crystals classifications, and many other related industries. In applying such systems, the main factors to consider are flowability (of material on equipment), deck screen inclination, angle of repose and mass throughputs or loading per total projected area of screen.

Flowability is the ability of granular solids and powders to flow (Datta, 2012). It is important to note that flowability is not an inherent material property, but rather a combination of the physical properties of a material (particles) that affect its flow on another material (equipment used for handling, storing or processing). It follows, therefore, that consideration must be given to both the material and the equipment. Consequently, flowability has been defined more accurately as "the ability of the powder to flow in a desired manner in/on a specific piece of equipment" (Xiaowei et al., 2012).

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Nomenclature

A	effective (free) screening area, m^2
a	distance from the center of mass to the rotational axis, m
D_{ap}	diameter of apertures, m
D_p	particulate diameter, m
g	gravitational acceleration, 9.81 $m\ s^{-2}$
m	mass of individual particles, g
I	moment of inertia of the particle, expressed here as a function of sphericity, $kg\ m^{-1}\ s^{-2}$
$M_{1...4}$	masses of particles collected on 1 mm, 2 mm, 3 mm and 4 mm sieves respectively, g
M_T	batch masses, g
M_{un}	mass of un-separated particles, g
m_o	mass of oversize particles, g
m_u	mass of undersize, g
M_{T_S}	simulation batch mass, g
M_{U_s}	simulation undersize mass, g
P	momentum, $kg\ m\ s^{-1}$
R	classification rate, $g\ s^{-1}$
t	simulation run/elapsed time, s
T	runtime taken by the mass, M_T to be separated, s
$\bar{v}$	bulk particulate velocity, $m\ s^{-1}$
v_{rel}	relative velocity of undersize to the oversize
$\emptyset$	Waddell sphericity index, dimensionless
η	classification efficiency, dimensionless
θ	tilt angle of the screens, °
Ψ	mass loading coefficient, dimensionless
α_c	linear acceleration of the center of mass of the particulate, $m\ s^{-2}$
α	angle of repose
ε	fraction of oversize to total batch mass, dimensionless
κ	constant of moment of inertia for near spherical particles, dimensionless
τ	screening rate constant, $s\ m^{-2}$
μ	coefficient of kinetic friction between screen surface and particulate, dimensionless

Another equally influential factor affecting screening is the angle of repose (α). By definition, the angle of repose is the angle between the horizontal and the slope of a heap of granular material dropped from some designated elevation (Ganesan et al., 2008). Screen inclination and/or mechanical agitation (such as vibration) are employed to enhance the flowability of the material and to improve the screening efficiency (Li et al., 2003), by modifying the angle of repose. Often as not, gravitational force is sufficient to cause necessary flow, when the right operating conditions are met.

Reducing inclination of the surface on which the particles are poured has the same effect as increasing the angle of repose; a situation that can better be visualized by considering the Carney funnel Fig. 1. In general, excellent flowability is achieved at low angles of repose (Ganesan et al., 2008; Bodhmage, 2006) or at higher inclinations, as can also be seen from the Carr classification of flowability by angle of repose. If the surface is not horizontal, h would be diminished, as the particles will flow down, and so the angle of repose is as seen in Fig. 1, and therefore higher flowability is achieved (Möller et al., 2002). Angle of repose, α can be estimated from the following Eq. (1).

$$\alpha = \tan^{-1}(h/r) \tag{1}$$

where h is the vertical height of the heap, and r is the radius of the heap formed and α is the angle of repose.

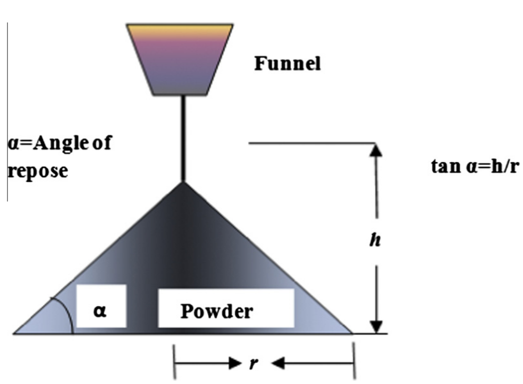

Fig. 1. Carney funnel used in measuring the angle of repose of particles less than 5 mm size, adapted from Datta (2012).

According to (Möller et al., 2002), glass beads of sizes ranging from 53 to 75 μm have α of 34 ± 1°, while relatively larger beads of sizes ranging from 0.5 to 0.75 mm have α of 22 ± 2°.

The models formulated in this study are a combination of phenomenological and numerical models based on Newtonian classical mechanics. The extent of difficulty to develop specific models is understood as an enormous and complex exercise. Certain bulk solid properties might be a reason why solid classification, old as it is, has not been fully understood to date (Chen et al., 2010; Li et al., 2003; Liu, 2009; Wang and Tong, 2011; Kruggel-Emden and Elskamp, 2014). Different materials have different properties and are thus unique and difficult to fully characterize, hampering the development of specific models for each of the materials. Models approximating system behavior are thus valuable for estimation and informed decision-making.

In this paper, we present experimental results on the effects of screen inclination on solids classification carried out on the prototype designed in Rotich et al. (2013); we also fine-tune the original models to reflect the realities of the experimental results. The formulated particle velocity models were solved by linear simulation, and found to behave similar to a linear time-varying system. Further trials however revealed that even though the motion of solid particulates along the inclined sieves may be linear, governing equations might not necessarily be linear functions of time but rather higher order nonlinear system that can be solved implicitly as ordinary differential equations (ODE).

It was concluded in Rotich et al. (2013) that there was no generation or degeneration of particulates, $dm/dt \approx 0$ during the classification process. However, upon further experimentation, it became apparent that some particles either got attached to and blinded the screens or flew off and hence could not be quantified as properly belonging to the undersize or oversize groups, which were the only groups covered by the model. It is important to note that these 'changes' in mass do not necessarily contradict the validation of the models, since there is no net increase or decrease in the mass of each particulate, but rather a temporary displacement from the two groups.

The objective of the current work is first to explore further insights into the theory of dry solids classification both individually and in bulk, especially the classical mechanics aspects involved. Secondly, the study aims to improve the operation of solids screening by refining and simulating the models developed earlier. This improved knowledge would help in identifying important