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Development of a geometric flight unloading model for flighted rotary dryers

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ABSTRACT

Flighted rotary dryers are used extensively in industrial applications for the drying of granular materials, and the understanding of the unloading characteristics of the flights within these units is critical to understanding their behaviour. This paper presents the development of a geometrical derived model for the unloading profile of a generic two-section flight. This model is then validated using experimental data from a flight unloading apparatus. The model is shown to be able to accurately reproduce the observed unloading profiles, however the results are shown to be highly sensitive to the material surface angle used in the model. High-speed photography is used to observe the surface of the granular material during unloading and measurements of key properties are made. Observation of these high-speed images shows that the unloading of the flight is discontinuous, and that there are significant fluctuations in the behaviour of the discharging solids.

1. Introduction

The drying of particulate solids is of great importance to a number of industries, such as sugar, grains, minerals processing and pharmaceuticals to name a few. One of the most common methods for drying large quantities of particulate solids is the use of flighted rotary dryers. In a flighted rotary dryer, solids are lifted by flights attached to the internal wall of a rotating cylinder, which lift the solids in the upper portion of the drum where they are released to form falling curtains of solids. In order to accurately predict the transport of solids and the drying that occurs within a rotary dryer, it is necessary to understand the behaviour of the solid material within a flight and the way in which the material is discharged. There are numerous mechanistic models for flighted rotary dryers in the literature that require this information to determine both the residence times and the material flow rates (Sheehan, Britton and Schneider [1] and Wang et al. [2]). The modelling of the rate of discharge of solids from rotating flights is the focus of this paper.

Hodgson and Keast [3] performed experiments in order to measure the unloading rate of the flights of an industrial sugar dryer at different points around the circumference of the dryer. The mass flux at specific locations along the horizontal axis of the dryer was calculated by measuring the amount of time taken to fill a collection vessel at each location. This data was then used to calculate the unloading profile of the flights.

Baker [4] proposed a geometric model for the solids holdup within three different types of flights. Baker's model calculated the solids holdup based on the dryer and flight geometry and the solid's dynamic angle of repose. Baker demonstrated that this model could be used to estimate the number of flights that should be fitted within a dryer.

Kelly [5] calculated the flight unloading profile by evaluating the solids holdup in a flight at discrete locations around the circumference of a dryer. By calculating the change in solids holdup between locations, Kelly approximated the unloading rate of the solids, and used this to study the distribution of solids across the dryer cross-section. Based on these observations, Kelly developed a theoretical flight geometry (referred to as an Equal Angular Distribution (EAD) flight) that would achieve a uniform distributions of solids across the dryer. Unfortunately, the shape of the openings of these flights was somewhat impractical when dealing with sticky solids which are commonly processed in flighted rotary dryers. Kelly [5] also experimentally measured the mass holdup in a flight as it travelled around the circumference of the dryer. Photographs were taken of a flight at different points around the circumference of the drum, and geometric calculations used to determine the mass holdup of the flight at each point.

Sherritt et al. [6] developed a simple geometric model based on the length of the material surface within a flight and the rate of rotation of the flight. However, Wang et al. [2] demonstrated that this model introduced significant errors due to oversimplification of the geometric analysis used to calculate the cross-sectional area of material in the flight.

Wang et al. [2] developed a model for the unloading of a two-section flight based on a geometric analysis of the material within the

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flight. Wang et al. calculated the cross-sectional area of solids (A) contained within the flight as a function of flight location (ψ), solids bulk density (ρ_b), rotational velocity (ω) and material angle of repose (ϕ), and used this to determine the discharge rate (F) from the flight using Eq. (1). Wang et al. assumed that the material surface was defined by the solids dynamic angle of repose at the flight tip, neglecting the presence of any material flowing over the flight tip. These predictions were not validated with experimental data, and the geometric arguments were not presented.

$$F = -\rho_b \omega \frac{dA}{d\psi} \tag{1}$$

Flight discharge rate based on cross-sectional area of solids [2].

Revol et al. [7] further developed the previous work done in this field, developing correlations to determine the solids holdup in a flight with any number of segments. These correlations were then used to develop equations for the solids flux across the drum, and the power required to lift the solids and rotate the drum. The predictions of these equations were then compared to photographic experimental data from a pilot-scale apparatus using a method similar to that used by Kelly [5]. Revol et al. reported that although the correlations developed could accurately predict the power required to operate the dryer, the predicted discharge rate differed significantly from the measured discharge rate [7]. This difference was attributed to uncertainties associated with the dynamic angle of repose [7].

All methods to model flight unloading to date have assumed that the material surface is free flowing and defined by a single characteristic angle of repose. However, studies in the physics of the flow behaviour granular solids have demonstrated that these materials often fluctuate between a stable and an avalanching state. Bagnold [8] observed that the surface angle of a granular solid could be increased beyond the angle of repose of the material whilst remaining stable. Bagnold observed that an “angle of maximal stability” existed for granular materials, several degrees larger than the angle of repose, beyond which the material surface becomes unstable and avalanches appear. Numerous other authors [9–12] have studied this phenomenon, and a number of fundamental models exist for predicting the behaviour of these systems. In terms of modelling the unloading of flights within rotary dryers, this suggests that unloading will be discontinuous, and that the material surface will vary between the materials angle of repose and maximum angle of stability.

Despite the importance of the flight unloading process on the behaviour of flighted rotary dryers and modelling these devices, no experiments have been performed to directly measure the unloading rate of full-scale flights. Furthermore, no observations have been made of the behaviour of the material surface during the unloading process. In this work, the authors present the derivation of a geometric flight unloading model for two-stage flights in order to predict both the flight holdup and solids discharge rate. The predictions of this model are then compared to experimental results from full-scale flight discharge experiments. Both mass unloading rate and free surface photography are used to validate the model and to determine the reliability of commonly held assumptions of flight unloading.

2. Geometric unloading model

Physical studies into the flow behaviour of granular solids [8–12] have shown that granular solid materials fluctuate between a stable and an avalanching state when inclined. Whilst it is possible to theoretically model the exact behaviour of these materials using particle–particle interactions, the computational requirements of such a model are significant. Thus, for the purposes of the model developed in this paper, the material surface will be assumed to be characterised by some mean surface angle (ϕ) which lies between the material's dynamic angle of repose and maximum angle of stability.

In a generic two-section flight with straight edges and no serrations, the material should form a cross-section such as that shown in Fig. 1. To characterise a two-section flight, it is necessary to know the number of flights within the dryer (N_f), the lengths of the two sections of the flight (s_1 and s_2), the angle at which the flight is attached to the wall (α_1) and the angle of the flight tip (α_2), as well as the radius of the drum (R). The model presented here assumes that material is held up in the flight such that the material surface begins at the tip of the flight and has a slope equal to the mean surface angle of the material (ϕ). Thus, knowing the bulk density of the solids, the holdup of the solid material within the flight can be calculated, at any point around the dryer circumference.

In most situations, flight are attached perpendicularly to the wall, i.e. $\alpha_1 = 90°$. Thus, for simplicity, this paper considers only flights where this is the case. Readers are referred to Lee [13] for a more generic description, including the circumstance where there is interference from the flight above. While mass can potentially leave, a flight at any point around the circumference of the dryer, the main area of interest in terms of solids transport is in the upper half of the drum. It is in this part of the drum that the solid material is released to form the cascading curtains where heat and mass transfer occur, the ultimate aim of work in this area being to optimise these phenomena. The model described here is limited to this part of the dryer.

It can be observed that the unloading of a two-section flight can be described by geometric phases defined by the intersection of the material free surface with the wall of the drum and the base of the flight, as illustrated in Fig. 1. The first phase occurs from the intersection point, point I, which lies on the drum wall. The bounds of this phase are defined by the base of the next flight in the dryer, and the base/wall intersection of the current flight (point a in Fig. 1). The second phase of unloading will then continue until the flight has released all the solid material, and the intersection, point I, coincides with point b in Fig. 1. In some dryers with closely spaced flight or materials with high angles of repose, a third phase of unloading may exist when the flight is full. In these situations, the material surface may intersect with the base of the next flight in the dryer, resulting in a lower cross-sectional area. Although unusual, this case is also shown in Lee [13].

These transitions between different phases of unloading result in sudden changes in the unloading behaviour of the flight, which appear as peaks in the unloading profile of the flight. This results in discontinuities in the derivative of the unloading rate, thus it is difficult, if not impossible, to develop a single equation for the

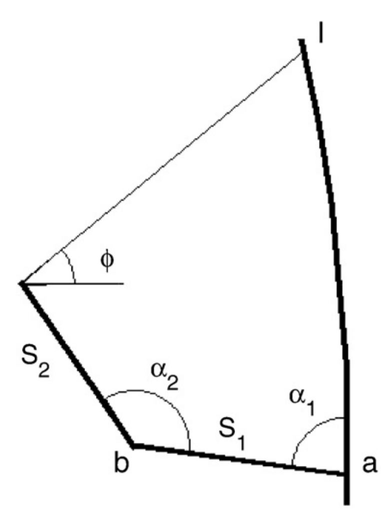

Fig. 1. A generic straight 2-section flight showing the intersection point I.