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Influence of flight design on the particle distribution of a flighted rotating drum

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HIGHLIGHTS

- Optimal design of flighted rotary drum is discussed under no gas flow conditions.
- Influence of flight length ratio on the flight cascading rates is studied.
- Extended geometrical model is developed for the height of the curtains.
- Effect of flight number is studied on the total particle surface area.

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ABSTRACT

Rotary drums, installed with longitudinal flights are often used to dry/cool granular materials in large quantities. Performance of such drums greatly depends on the uniform distribution of the particles over the drum cross section, which is attained by an optimal design and allocation of the flights. In this study, a mathematical model has been developed for the rectangular flight to optimize the total particle surface area which is a function of the cascading rate and falling time of the particles. The falling time in turn is a function of curtain height and can be estimated by geometrical analysis. Influence of the number of flights and the flight length ratios has been studied. It was observed that, as the flight length ratio increased the cascading rate decreased during the initial discharge, but increased rapidly at higher discharge points resulting in a bulk movement of the solids, which also determines the density of the curtains. Experiments were carried out to validate the developed model with a drum of 500 mm in diameter and 150 mm in length. The experiments were performed with different flight profiles and flight numbers (12 and 18). Good agreement was found between the experiments and the model predictions.

1. Introduction

Drying of granular matter is important in food, mineral, metallurgical, and in chemical industries. Rotary dryers are commonly used for drying the granular materials in large quantities. They are equipped with flights on the interior of the drum in order to elevate the material and shower it over the cross section, which improves the contact surface area between the hot gases and the wet solids. The quality of the end product primarily depends on the time spent by the material against the hot conditions during the transport from the upstream end to the downstream end of the dryer. It is mainly controlled by the flight design and the drum inclination.

In general, different flight configurations such as rectangular, angular, and extended circular flights are in practice for granular materials in industry (Krokida et al., 2007). It is a difficult task in industry to operate flighted rotary drums with full performance due to the difficulties during the handling of powders and sticky materials. For a given dryer dimension, the material should be uniformly distributed over the drum cross section during the active phase in order to produce a quality end product. The performance of the drum greatly depends on the surface area responsible for the heat and mass transfer, which is a function of the quantity of material in the airborne phase. Hence, the cascading rate of the flights and the drum loading determine the amount of material that is exposed to the hot gas flow, the calculation of which is the main objective of the present study.

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There are three different states of the drum loading that can be observed within the rotary dryer, which are characterized based on the first unloading of the flight (Matchett and Baker, 1987). If the flight discharge starts when it is in the upper half of the drum, it is said to be under-loaded. Under such conditions, the time spent by the particles in the airborne phase is minimum, which can lead to smaller residence times than required. As the loading state of the drum is gradually increased, first unloading position of the flight is ultimately decreased and at some point the unloading starts when the flight tip is at 0°. At this point the drum is said to be design-loaded. In this case maximum amount of material is distributed in the air-borne phase, hence the maximum heat transfer can be expected between the solids and the hot gas stream. Further increasing the feed rate does not increase the airborne solids, but the flights are completely crowded with the material which is defined as over-loaded drum. In this case, the discharge of the material starts immediately as the flight tip detaches from the bed surface.

There are numerous studies available in the literature to predict the heat transfer between the hot gas and solids. The key parameter that mainly controls the gas to solid heat transfer is the cascading rate of the flight (Saeman and Mitchell, 1954). It involves predicting the total particle surface area that is chiefly responsible for the heat and mass transfer. It can be regulated either by varying the Froude number of the drum or the flight length ratio. In general, industrial rotary drums operate at low Froude numbers due to the higher operational costs at higher rotational speeds. Therefore, the other possibility is to vary the flight length ratio in order to achieve optimal cascading rates giving a better performance. No major predictions were carried out till now to address the surface area of the particles that is in contact with the hot gas.

Saeman and Mitchell (1954) developed a relation for the volumetric cascade rate which was studied against the heat transfer coefficient in order to estimate the performance of the dryer. The estimated heat transfer factor was observed to decrease as the number of rotations increased. This was due to the fact that the air-material entrainment ratio decreased as the curtain density had increased. However, the variation of cascading rates due to the change in flight length ratios was not investigated. According to Porter (1963), the concentration of the falling curtains in the gas stream depends on the ratio of cascading rate (ft^2/min) to the exposed surface area of the series of curtains (ft^2). However, this ratio should not exceed 1.3 min^{-1} but it can be higher based on experience.

Friedman and Marshall (1949) developed an empirical relation for the volumetric heat transfer coefficient and studied the influence of number of flights, rotational speed, and the feed rate for different materials. The volumetric coefficient was observed to be smaller when no flights were used, significant improvement was observed when the number of flights was increased to two and four. No rapid change was observed when increasing the flight number to eight. Heat transfer analysis of the curtain falling in a gas stream was studied by Wardjiman and Rhodes (2009). Wang et al. (1995) proposed a relation for the optimization problem to achieve a maximum drying efficiency, by maximizing the cascading rate of the flight and the curtain width. According to Blumberg and Schlünder (1996), the performance of the dryer mainly depends on the contact area between the particles and the hot gas, which depends on the distribution of the material over the dryer cross section. The effective transfer area was calculated based on the height of fall and the number of flights. They proposed a semi empirical relation for the mean height of fall as a function of the drum filling degree and flight length ratio. However, the valid range of the filling degree was observed to be too high for the industrial application. The average approach technique was applied by Glikin (1978) to predict the mean height of fall.

Numerous studies were published related to the prediction of the dense phase of the flights. Glikin (1978) formulated the holdup of a single rectangular flight as a continuous function of the discharge angle. Lee and Sheehan (2010) developed a geometrical model for the angular flights and validated it with experiments of a flight attached to a shaft. Van Puyvelde (2009) studied the effect of a complex flight geometry on the holdup and flight cascade rate. He predicted that more lifting of the material was possible with the complex flight profiles than with simple lifters. The cross sectional area was measured from the image analysis and compared with model predictions. Revol et al. (2001) presented a model to predict the holdup and solids flux for three segmented flights.

A two stream model was developed by Matchett and Baker (1987) in order to obtain a relation for the mean residence time of the particles in the drum. This was done by subdividing the material into two phases: airborne phase and dense phase. The flight borne solids and the solid bed at the bottom were considered as one single dense phase. However, this treatment was not sufficient enough to represent the behavior of the drum. Since, with this approach it is difficult to determine the quantity of material in the non-discharging flights accurately. Also, the authors neglected the bouncing and kilning mechanisms which are more dominant in under-loaded and design-loaded drums. Further, they also obtained a transition point from the experiments between the under-loaded and over-loaded drums, where this transition region was considered as the condition for design-loaded drums (Matchett and Baker, 1988). Sherritt et al. (1993) proposed a model to estimate the contribution of each phase (dense phase of the solid bed, dense phase of the flights, and air borne phase) for over-loaded and under-loaded drums based on the surface length of the flight. The total holdup of the material at any cross section becomes the sum of the holdups of each phase. In a recent study, Ajayi and Sheehan (2012) proposed a method to estimate the design load of the flighted rotary drum experimentally using image analysis techniques. The design load condition was presumed to be the point of loading where the cross sectional area of initial discharge of the flight was saturated. They also presented an approach to determine the airborne phase by measuring the cross sectional areas of all the curtains the voidage of which they obtained from CFD simulations. It was found that the material in the air borne phase increased as the rotational speed increased.

The aim of the present work is to develop a theoretical model for the optimal design of the rectangular shaped flights under no gas flow conditions by maximizing the total surface area of the particles in the airborne phase. For this purpose, the curtain height was predicted over the flight discharge based on a geometrical model. The region of discharge was divided into two sectors where the particles impact on the bed surface in sector 1 and on the flight sheet in sector 2. Further, the filling degree (holdup) of each phase was determined as a function of the flight length ratio and compared with measured data for over-loaded drums.

2. Model development

2.1. Model assumptions

- Free flowing and non-cohesive material.
- The drum is assumed to be either design or over-loaded.
- Uniform axial profiles and no gas glow.
- Free and vertical fall of the particles from the flight tip (vertical drag and axial drag are neglected).