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Solids holdup in flighted rotating drums: An experimental and simulation study

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ABSTRACT

Directly heated rotary dryers are widely used in various industries and have been the subject of numerous studies. However, few studies have focused on the behavior of particle dynamics in these dryers, and most of them are still designed based on empirical data and pilot plant scale-ups. This paper reports on a study of the effect of operating conditions on solids flow in rotating dryers. The holdup of solids in the flights was modeled using the Eulerian Granular Multiphase Model and the results were compared with experimental data, using a methodology created specifically for this purpose. The influence of particle diameter, type of material, rotation speeds and drum loading on solids holdup in the flighted rotating drum has been analyzed. The results of the present work have shown that the Eulerian approach has been able to predict the fluid dynamics behavior of different solid materials in several operating conditions. Despite the deviations between predicted and measured results, this approach allows the development of a "more" generalized model, with "low" computational cost.

1. Introduction

Rotary dryers are used in a variety of industrial settings, such as the mineral, food and chemical industries. For example, in the production of granulated fertilizer [1], one of the materials used in this work, the drying, that occurs after granulation, is performed in rotary dryers and consists of one of the most energy-intensive operations [2]. Compared to other types of dryers, these are the most commonly used devices due to their flexibility in operating with different types of materials. However, the rotary dryers are a significant capital item for many industries. Their thermal efficiency is strongly dependent on the correct design and operation [3].

Numerous research efforts have focused on characterizing the dynamics of rotary dryers [4], but the design of these devices is complex and still is dictated by the "experience" of engineers and empirical factors. Therefore, theoretical studies are necessary to gain an in-depth understanding of the dynamics of particles in these dryers [5].

Ideally, a rotary dryer should be operated such that every flight was filled to its capacity, allowing for the maximum amount of solids to be curtained at any point. Underloaded (insufficient solids to fill the flights) or overloaded (more solids than the flights can carry) are undesirable conditions, since the dryer will be operating with low capacity or with limited contact between solids and hot air [3]. Depending on the position in which the first discharge from the flights occurs, the drum can be classified as underloaded, design loaded or overloaded [3,6]. These conditions are determined by several factors, such as operating conditions, properties of the material, and geometric configuration of the flights and drum [6].

The design load condition is assumed to represent the point of operation where there is maximum interaction between the drying gas and the airborne phase. The kilning or rolling solids do not participate in drying to the extent that airborne solids do, which results into poor efficiency of the dryer [7]. If the dryer is operating in an underloaded condition, the first discharge will occur after the 9 o'clock position (for a clockwise rotating drum, Fig. 1), obtaining retention time below the required drying time, as well as a low capacity condition. When the first discharge occurs before the lifting flight reaches the 9 o'clock position (angular position of flight tip of 0°), the drum is overloaded, and the excess material rolls in the base of the dryer with poor solid–air contact. Therefore, in the design loaded condition, the discharge from the flights occurs precisely in the 9 o'clock position, which is the condition in which the maximum interaction between the drying air stream and the airborne particles occurs [7].

Many potential benefits, such as energy savings, can be obtained through a proper design and operation of these dryers. However, the design and simulation of rotary dryers are highly challenging due to the complex fluid dynamics behavior. The combination of particles being lifted by the flights, sliding and rolling, then falling as a rain of particles, is very hard to analyze. Thus, the fluid dynamic study of these devices, can be performed without the presence of drying air, which makes it easier to understand how the particles in these devices move.

With the advance of technology and the increasing processing power of computers, CFD has become a very useful tool for describing

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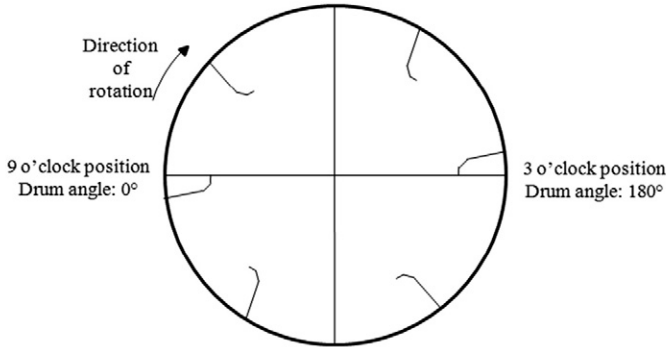

Fig. 1. Angular positions of the flight around the drum.

flows, especially in the field of gas–solid flow. This technology, allied to experimental data, that validate models, can provide satisfactory simulation results for various processes [8].

The Euler–Euler and Lagrangian approaches are commonly used to simulate particle dynamics [9]. The Lagrangian approach is based on the particle–particle interaction forces, while the Euler–Euler approach treats the phases mathematically as continuous and interpenetrating. The Lagrangian approach, which is used in the Discrete Element Method (DEM), has already been employed in several simulation studies of flighted rotating drums [5,10–12]. In this approach, each particle trajectory is calculated considering all the active forces, providing information about particles at the microscopic level and describing the individual trajectory of a particle. On the other hand, the DEM has a crucial problem – its computational cost, which is directly proportional to the number of particles in the process, making it difficult to simulate large-scale processes, as well as requiring a large number of parameters to describe the process. The Euler–Euler approach does not allow for the description of individual particles, because the phase containing the particles is treated as continuous and the properties of particles are calculated based on the kinetic theory of granular flow. Nevertheless, the computational cost of this approach is lower, and large-scale processes can be simulated using fewer defined parameters.

Numerical simulation studies by using Euler–Euler approach along with the kinetic theory of granular flow have become popular in the field of gas–solid flow, in several applications (fluidized beds, spouted beds, hydrocyclones, rotating drums and other systems) [12–17]. The basic idea that governs the granular kinetic theory is that the grains are in a state of continuous and chaotic restlessness within the fluid. This chaotic random motion exists at very low concentrations (due to friction between gas and particles, gas turbulence, pressure variation in the fluid, etc.) or at higher concentrations (due to grain collisions) [14]. Some authors have used the Euler–Euler approach to study the behavior of a curtain of particles falling through a horizontal gas stream [6, 18]. However, no studies have used this approach to describe the behavior of particles in a flighted rotating drum. Therefore, a novelty of the present work is the use of the Euler–Euler approach to simulate the movement of particles in a flighted drum.

Despite the development of numerous geometric flight unloading models for flighted rotary dryers [19–22], most of these models are non-generic and developed based on a particular type of flight configurations, besides the computational costs for large equipment are very high. The Eulerian approach allows the development of a "more" generalized model with low computational costs. When one model is validated, it can be applied to many different geometries and number of flights, with no need to develop another model.

As solids holdup in the flights cannot be "measured" directly by FLUENT® software operating with the Euler–Euler approach, in the present work, a method was developed to estimate solids holdup in the flights as a function of the angular position of the tip of the flight, using the flow profiles obtained in the simulations.

The objective of this paper was to analyze the effect of some operating conditions (rotation speeds and drum load) on the fluid dynamics behavior of different solid materials (free flowing) in a flighted rotating drum, from simulation and experimental studies. Unlike other literature studies, in the present work the simulations have been performed using a Eulerian approach.

2. Experimental setup

The experimental apparatus used in this work consisted of a flighted rotating drum. The cylindrical part and flights were made of stainless steel. The front end plate was transparent for easy observation of flow profiles. This side of the drum was equipped with a protractor, that enables to trace a horizontal and a vertical line, as shown in Fig. 2, to measure the angular position of the tip of the flight. The opposite side had an acrylic particle collector to collect the particles in each angular position.

The experiments were carried out in a drum equipped with six lifting flights, each having three segments, as can be seen in Fig. 2. The drum had an inner diameter of 10.8 cm and a length of 50 cm. The size of the segments was L1 = 0.01 m, L2 = L3 = 0.004 m, their length was 50 cm, and they had an inter-segment angle of 135°. The small scale drum facilitates experimental and simulated measurements. The rotation speed of the drum was controlled by means of a frequency inverter and measured using a laser tachometer.

The particles used in this experiment were glass beads and granular single superphosphate (SSP) fertilizer. The three different glass beads had mean diameters of 1.09, 1.84 and 2.56 mm and a bulk density of 2455 kg/m^3. The porosity of the packed bed was 0.37 for these particles. Drum rotation speeds of 1.5, 3 and 4.5 rpm were used in the experiments. The granular SSP fertilizer had an average diameter of 2.56 mm and a bulk density of 2090 kg/m^3. The packed bed using fertilizer had a porosity of 0.51.

The angular position of the tip of the flight was measure using an image analysis method. A camera was placed on a tripod on an exactly horizontal plane, and the images it recorded were used to measure the angle between the line formed by the tip of the flight and the origin and the horizontal axis, traced as in Fig. 2. These measurements were taken using ImageJ® software. Thus, when a flight reached a given angular position, the rotational motion was stopped and a photograph was taken to measure the position using ImageJ®. The particles were then collected from the flight and weighed on an analytical balance. With this procedure, the solids holdup in the flights was measured as a function of the angular position.

Another experimental apparatus has been used, to measure the particle–particle internal angle of friction that is roughly the same as the particle static angle of repose for free-flowing particles, named as β. The static angle of repose is determined by lifting an inclined particle attached lane with free particles on it. When the particles start rolling down the plane, the plane inclined angle is used as the angle of repose of the particle [9]. The measured values of static angle of repose were $28° \pm 0.6°$ for the glass beads of 2.56 mm diameter and $41° \pm 0.8°$ for SSP fertilizer of the same diameter.

3. CFD simulation

Solid–gas two phase particle dynamics in a rotary dryer was simulated using the Eulerian Granular Multiphase Model. Thus, the flow was described using the Euler–Euler approach along with the Kinetic theory of granular flow.

3.1. Conservation of mass and momentum equations and drag model

The kinetic theory of granular flow, developed by Lun et al. [23], has been used to model the solid phase stress ($\overline{\overline{\tau_s}}$). This theory is an