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# Transverse flow at the flight surface in flighted rotary drum

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ABSTRACT

Rotary drums, installed with longitudinal flights are often used to dry/cool granular materials in large quantities. The rate of solids falling down from the flights determines the amount of material responsible for the contact between the solids and hot air stream, which primarily depends on the angle of repose at the flight surface. In this study, the model of Schofield and Glikin has been extended by considering a flowing layer at the flight surface and inertial force acting in the cascading layer due to the rotation of the drum. The corresponding velocity profile for the layer has been predicted by following the Eulerian approach by treating the granular flow as a continuum similar to the transverse flow in rotating drums without flights. To validate the model, experiments were carried out at a laboratory drum of 0.5 m in diameter using quartz sand, glass beads and steel balls of different particle sizes at various drum rotations. The measured data is compared with the model predictions under different experimental conditions. The experimental data showed good agreement with the model predictions.


## 1. Introduction

Rotary drums equipped with internal flights have a great importance in sugar, mineral processing, metallurgical, and in chemical industries. These drums are commonly used for drying or cooling the particulates in large quantities. The flights are installed to the interior of the drum in order to improve the contact between the hot gases flowing in an axial direction and the wet solids. The quality of the end product primarily depends on the time spent by the material against the hot conditions during transport from the upstream end to the downstream end of the dryer. It is mainly controlled by drum speed, flight design, drum inclination, properties of the material, and the flow properties of the gas. Drum speed and the flight dimensions regulate the cascading rate of the flights which in turn controls the amount of material distributed in the air-borne phase of the drum. All the parameters mentioned above determine the retention time of the material in the drum. Heat and mass transfer are mainly effected by the area of the material exposed to the hot or cold conditions in the dryer/cooler. The prediction of this contact area is, therefore, essential for modeling the dryer/cooler. As will be shown this can be achieved by a geometrical approach.

Numerous contributions have been made during the last few decades in the context of flight unloading studies by determining the quantity of material in the flight [1–6]. Various sets of equations were developed to determine the flight holdup for angular and extended circular flights [7]. Kelly [8] further extended this approach by proposing a theory of equal angular distribution. In this approach of the flight design, an equal distribution of particles to cascade over the region of the flight discharge was considered by taking a constant surface angle over the flight discharge. An ideal and complex flight shape was proposed in this context. However, the flight geometry proposed is impractical. Revol et al. [9] further extended the approach from Kelly [8] by proposing model equations for three segmented flights. The power required to lift the solids was accurately predicted based on the flight hold-up. However, the measured unloading rate showed a large deviation from the predicted unloading rate of solids. This is attributed due to the assumption of a constant surface angle. Wang et al. [10] developed a differential approach to predict the behavior of the flights with arbitrary geometry, and an outline was also proposed to achieve the maximum drying efficiency. However, the unloading rate predicted in his study deviated from the measurements by 33% which is not acceptable. Blumberg and Schlünder [11] developed a normalized model by assuming linearity of the flight holdup with the angular position to depict the discharge characteristics of particles. Van Puyvelde [12] instrumented a model to describe the behavior of complex geometry flight profiles. He stated that an inclined flight occupied more material than flights whose radial length was perpendicular to the drum wall. In all these studies, the flight holdup depends on the surface angle of the flight to the horizontal termed as the kinetic angle of repose ($\gamma$). Schofield and Glikin [13] were the first who developed a relation for this angle from the equilibrium of gravitational, centrifugal, and frictional forces at the flight tip by neglecting the inertial force. For this purpose, a negligible thin active layer was assumed at the flight surface, although, the active layer at the flight tip already has a thickness of a few particles. The resultant forces balance equation was

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validated using an experimental drum filled with pumice granules [2], by taking the photographs of the drum. The angles of repose were calculated from the resultant images and compared with the theoretical values. Porter [1] validated this equation for Froude numbers greater than 0.18 by mounting closed rectangular shaped boxes to the inner shell of the drum filled with 3 mm glass spheres. However, under practical conditions the operated range of Froude number is much lower.

The aim of the present study is to predict the kinetic angle of repose as this parameter is responsible for determining the rate of solids unloading from the flight. In the previous model of Schofield and Glikin, a single/thin layer of particles was considered in the cascading layer, and the inertial force acting on the rolling particles at the flight surface was neglected. A mathematical model was developed by considering a flowing cascading layer of few particle thicknesses at the flight surface similar to the case of rotating cylinder without flights by incorporating the inertial force based on the approaches followed by Mellmann et al. [14] and Khakhar et al. [15]. The velocity profile has been determined by treating the granular flow as a continuum. Experiments were conducted at a laboratory drum using various materials (quartz sand, glass beads, steel balls) of different sizes at different rotational speeds in order to validate the model.

## 2. Model development

### 2.1. Extended model of the kinetic angle of repose

The model of Schofield and Glikin [13] assumed only a single particle layer to exist at the flight surface while determining the kinetic angle of repose by including the centrifugal force and neglecting inertial force, although a flowing region exists similar to cascading layer in drums without flights. Better prediction of this angle is truly important since this parameter is responsible for determining all phases of motion in the drum. Therefore, in the present study the model of Schofield and Glikin [13] has been extended by considering an active layer at the flight (see Fig. 1) and also incorporating the inertial term [16]. The modified forces balance diagram for this case is shown in Fig. 2

$$F_F + F_I = F_G \sin\gamma - F_C \cos(\delta_c - \gamma), \quad (1)$$

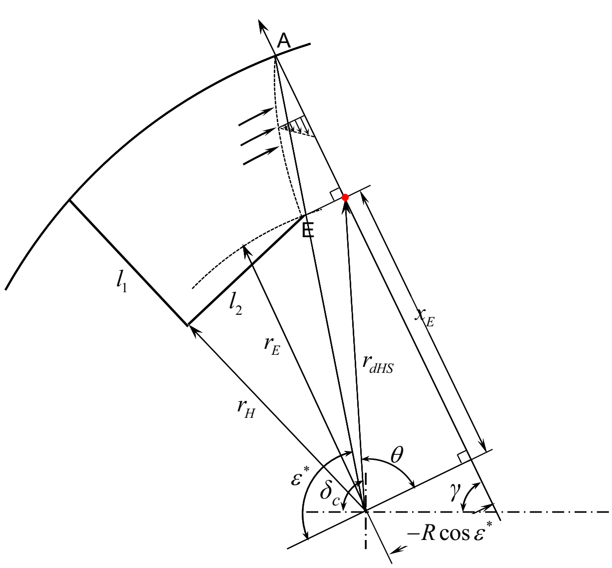


**Fig. 1.** View of transverse motion of particles in the cascading layer at the flight surface of flighted rotary drums.

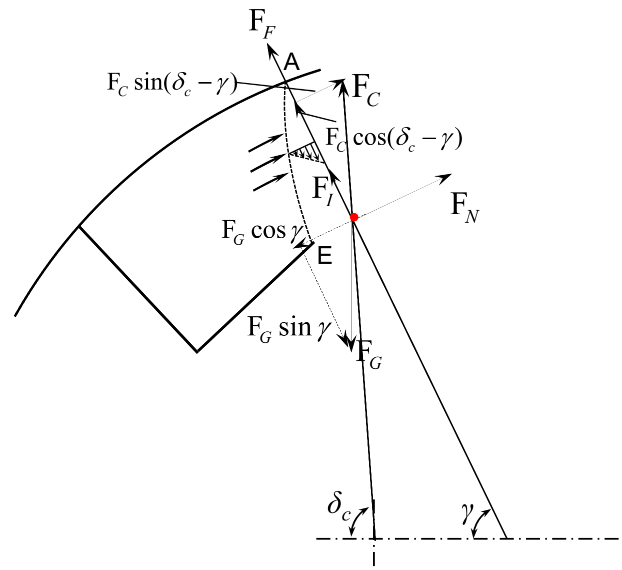


**Fig. 2.** Balance of forces acting on a particle in the active layer at the flight tip.

where $\delta_c = \gamma - \theta \pm 90$, '−' is for $\delta < \gamma$ and '+' for $\delta > \gamma$, and $tan\theta = x_E/(-R\cos\epsilon^*)$. The resultant force acting vertical to the bed surface is given by

$$F_N = F_G \cos\gamma - F_C \sin(\delta_c - \gamma). \quad (2)$$

The particles that are ready to fall from the layer over the flight surface will undergo centrifugal force

$$F_C = dm\omega^2 r_{dHS}, \quad (3)$$

where $r_{dHS}$ is given by

$$r_{dHS} = \frac{x_E}{\sin\theta}. \quad (4)$$

The flow motion at the flight surface induces an inertial force which can be expressed as [17]

$$F_I = dm\overline{v}_x \frac{d\overline{v}_x}{dx}, \quad (5)$$

where $\overline{v}_x$ is the average velocity of the particles in the active layer. After simplifications of the above equations and rearranging, the final form of the kinetic angle is given by

$$\tan\gamma = \frac{\mu + Fr\left(\frac{r_{dHS}}{R}\right)(\cos\delta_c - \mu\sin\delta_c) + Fr\frac{\overline{v}_x^*}{\cos\gamma}\frac{d\overline{v}_x^*}{dx^*}}{1 - Fr\left(\frac{r_{dHS}}{R}\right)(\sin\delta_c + \mu\cos\delta_c)} \quad (6)$$

where $\overline{v}_x^* = \frac{\overline{v}_x}{R\omega}$ and $\frac{d\overline{v}_x^*}{dx^*} = \frac{\overline{v}_x^*|_A - \overline{v}_x^*|_E}{x_A^* - x_E^*}$. The detailed description of the velocity gradient term is presented in the following section.

### 2.2. Analysis of transverse flow at the flight surface

The angle made by the surface of the material in the rotary drum with the horizontal is called the dynamic angle of repose (Θ). The bed remains stable until this angle approaches the upper angle of repose or the maximum angle of stability [18,19] and the avalanches begin when the dynamic angle exceeds this angle. The frequency of these avalanches increases as the rotational speed increases resulting in rolling motion. In a flighted drum, the material in the flight is tilted due to