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Transverse motion of cohesive powders in flighted rotary kilns: experimental study of unloading at ambient and high temperatures☆

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ABSTRACT

The transverse flow of cohesive powders in rotary kilns equipped with lifters was studied experimentally and theoretically. A laboratory device was built up in which the flow of uranyl difluoride (UO_2F_2), uranium sesquioxide (U_3O_8) and uranium dioxide (UO_2) powders was filmed, recorded and analyzed using partly manual image analysis techniques. Experiments were performed both at room temperature and at high temperature. A constitutive law describing the powder discharge was derived, involving a relationship between the volume fraction of powder contained in a lifter and the angular position of this lifter. This law based on geometrical calculations is successfully compared with the experimental results of unloading.

1. Introduction and Background to the Problem

For over a century [1], rotary kilns have been widely used in the inorganic chemistry industry. They are a key element in the production processes of cement, lime and pigments (titanium dioxide calcination) and in extractive metallurgy for the reduction of ore [2]. Rotary kilns are well suited for drying [3,4], for the pyrolysis of solid waste [5], and are also used to convert uranium fluoride into uranium dioxide for the manufacture of nuclear fuel [6–8].

Natural uranium cannot be processed directly because its content in isotope 235, the only fissionable isotope, is too low. To enrich the mineral, the uranium is therefore first converted into uranium hexafluoride (UF_6). Enrichment in isotope 235 is carried out in the gas phase, either by gaseous diffusion or by centrifugation. The depleted uranium is then converted into a chemically stable and insoluble oxide, U_3O_8, and stored. The enriched uranium is converted into solid UO_2 used to produce the solid fuel for nuclear power plants. Both processes are conducted in conversion kilns, which comprise a hydrolysis reactor and a rotary kiln fitted with lifters. Rotary conversion kilns are externally heated by resistors located close to the outside wall of the rotating cylinder, but they differ in size and nominal operating conditions [6]: the type of rotary kiln used for depleted uranium conversion is henceforth named “kiln 1”; the type of rotary kiln that converts enriched uranium is named “kiln 2.”

Various studies have been carried out on conversion kilns in an attempt to simulate their hydrodynamic, chemical and thermal behavior [6]. In this type of kiln, hydrodynamic, thermal and chemical modelling processes are closely linked, as it is clear that heat and mass transfer processes are strongly governed by the transverse flow of the powder (i.e., in a cross section of the kiln), which determines the quality and duration of gas/solid contact. In order to correctly model the operation of the kiln, it is essential to be able to calculate precisely the solid distribution at any point in the rotary kiln. Understanding the solid motion taking place in rotary kilns is therefore crucial.

Numerous publications describe the flow of a solid charge in rotary kilns; the most frequently cited concerning transverse motion are Henein et al. [9] and Mellmann [10]. Fewer studies have been devoted to the transverse movement of a solid charge in a rotary kiln equipped with lifters. A “lifter discharge law” (i.e., a relationship between the volume fraction of powder contained in a lifter and the angular position of this lifter) was first of all determined theoretically

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☆ Note: The results and calculations presented here were obtained in 1998 during a confidential study.

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and then verified experimentally. Based on this law, the gas/solid contact area and the mean residence time in the rotary kiln were calculated.

Thus, Kelly and O'Donnell [11] experimentally verified the law proposed by Schofield and Glikin [12], giving the "instantaneous angle of repose of particles in a flight" as named by Kelly and O'Donnell or "angle particles in flights make with horizontal" as called by Schofield and Glikin (what we henceforth name "avalanche angle" δ) as a function of the dynamic friction coefficient: Kelly and O'Donnell showed that for small enough rotational speeds, δ is constant for a given material whatever the angular position γ of the lifter. Based on the balance of forces, Blumberg and Schlünder [13] assumed that the surface of the powder in a lifter constantly forms the dynamic angle of repose θ_{dyn} with the horizontal (i.e., $\delta = \theta_{\mathrm{dyn}}$); they experimentally verified that the volume of powder contained in a lifter varies linearly with its angular position γ (see notations on Fig. 1a).

Several authors [14–18] used a description of the flight holdup with a constant avalanche angle as determined by Kelly and O'Donnell in order to predict the overall particle movement in flighted rotary drums (mean residence time and RTD); the experimental work carried out in some of these studies generally concerns measurement of the mean residence time and/or the RTD. Baker [3] or Kelly [4] proposed methods to determine by calculation the best shape and the optimal number of lifters for drying applications.

Sherritt et al. [19] proposed a method to calculate the hold up in a lifter. This method is not based on the avalanche angle but can only be applied to free-flowing granular materials.

A few authors [18,20–22] calculated a non-linear discharge law based on Kelly's hypothesis of a constant avalanche angle. The small number of experimental results reported in the literature concerns relatively coarse (usually on the order of a mm or more) and generally non-cohesive particles, such as sugar, sand, granulated fertilizers, adsorbent beads or flexible filamentous particles [23]. Lee and Sheehan [24] presented an experimental study of the effect of certain operating parameters on this non-linear discharge law for a single lifter. Ajayi and Sheehan [25,26] recently published experimental studies using image analysis techniques to determine the loading conditions of sand in the lifters of a dryer; the study focused on quantifying the airborne solids.

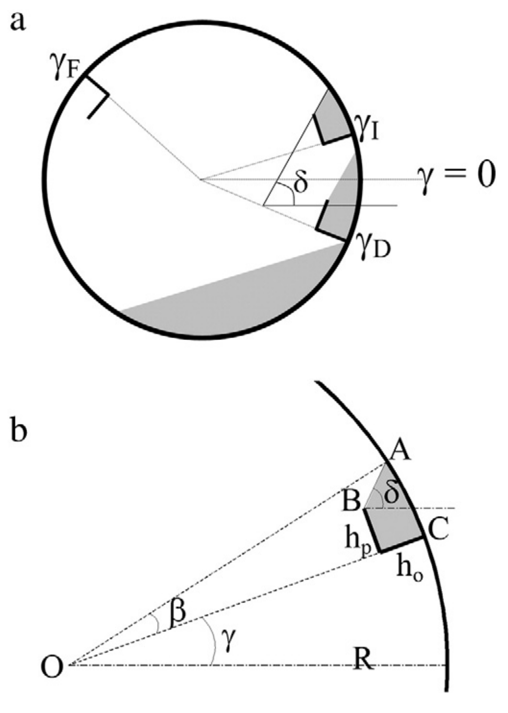

Fig. 1. Characteristic parameters for the (a) discharge law and (b) lifter parameters.

Sunkara et al. [27] has very recently published a method for the calculation of the discharge characteristics of rectangular flights identical to what we did in 1998 (see Appendix A), again with experiments on non-cohesive particles (sand and glass beads) of respectively 0.2 and 0.7 mm.

In the literature, "avalanche angle" δ and "dynamic angle of repose" θ_{dyn} are indeed often merged, but as will be shown in this work, these two angles are not equal for cohesive powders (weather they can be measured exactly).

With the development of image analysis techniques, it appeared important to measure the lifter discharge law experimentally rather than simply apply Kelly's hypothesis (i.e., a constant avalanche angle) to calculate this law (that is to say, measure the volume fraction of powder contained in a lifter and the angular position of this lifter, in order to establish a relationship between them). To the best of our knowledge, no paper has been published regarding the transverse flow of fine cohesive powders in rotary kilns equipped with lifters. Moreover, in the open literature, the experimental studies on lifter discharge have always been performed at ambient temperature, despite the fact that the behaviour of a cohesive powder under high temperature may be significantly different from that at room temperature. A key point in our paper is that the cohesive powders studied are those encountered in the manufacture of nuclear fuel. Furthermore, the influence of temperature on the behaviour of these powders is studied between ambient temperature and 790 °C.

We have also attempted to predict the law theoretically, from geometrical considerations. Knowledge of the lifter discharge law is particularly useful for studies of rotary kilns since it enables calculation of the fraction of powder that is lifted for given conditions, seeing that the mass transfer between solid and gaseous reagents is different from that in the bulk (which is continuously stirred through lifters). We also need to calculate the thermal transfer areas between solid and wall or solid and gas.

2. Experimental Method and Apparatus

2.1. Flow at Ambient Temperature

The transverse flow of various powders (UO_2F_2, U_3O_8 type 1 and type 2 and UO_2) was studied at ambient temperature using two experimental devices. The first one, denoted drum 1, represents a slice of kiln 1. The second, denoted drum 2, represents a slice of kiln 2. For both drums, the diameter and the internal equipment are the same as in the corresponding industrial kiln; the length is 0.3 m. The dimensions of kilns and lifters are given in Table 1. Each has a glass front to enable visual observation. They can be placed on a chassis equipped with a motor and speed variator and are installed in a closed ventilated cabin, as shown on Fig. 2. Filling and emptying operations are performed under hermetic glove-box conditions. Powder motion is filmed with a digital video camera through the glass window. The properties of the different powders are given in Table 2. It can be seen that the oxides are clearly cohesive (Carr's index is more than 0.4, and the Hausner ratio is more than 1.4); UO_2F_2 is on the borderline of highly cohesive powders.

The ranges of variation of the experimental parameters were chosen to cover the operating conditions of industrial kilns. The transverse flow of UO_2F_2 and U_3O_8 type 1 powders was studied thanks to

Table 1
Dimensions of the kilns.

	Inside diameter [mm]	Length [m]	Number of lifters	h_o* [mm]	h_p* [mm]
kiln 1	750	10.24	6	60	60
kiln 2	348	5.34	4	35	35

*See Fig. 1b.