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A hydrodynamic model for flighted rotary kilns used for the conversion of cohesive uranium powders

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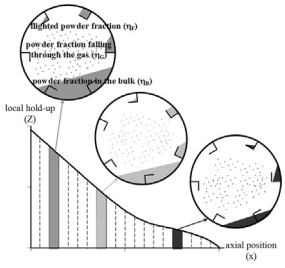
HIGHLIGHTS

- Transverse flow of cohesive powder in flighted rotary kiln was modeled.
- Axial bed depth profile was calculated from the Saeman–Kramers–Afacan model.
- Solid distribution was calculated from geometrical calculations and measurements.
- The fall velocity of the cohesive powder was measured at high temperature.
- The 'snapshot' obtained allows to calculate thermal transfer areas and mass transfer.

GRAPHICAL ABSTRACT

Axial and transverse distributions of cohesive powder in flighted rotary kilns used for the conversion of uranium.



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ABSTRACT

The axial and transverse solid distribution of a cohesive powder in flighted rotary kilns was calculated from an original method based on the lifter discharge law previously determined, geometrical calculations and supplementary measurements (in particular the fall velocity of the powder at high temperature). At a given axial position, the quantity of powder falling through the gas, the total quantity of flighted powder as well as the quantity remaining in the bulk are thus calculated; the axial bed depth profile is obtained from the Saeman–Kramers–Afacan model.

1. Introduction

For over a century (Meade, 1914), rotary kilns have been widely used in the inorganic chemical industry. They are a key element in the production processes of cement (Mujumdar and Ranade,

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Table 1
Nominal operating conditions of rotary kilns used.

	kiln #1	kiln #2
Inside diameter [mm]	750	348
Length [m]	10.24	5.34
Inclination [%]	2.5	2.5
Number of lifters	6	4
Lifter dimension normal to the kiln wall [mm]	60	35
Lifter dimension parallel to the kiln wall [mm]	60	35
UF_6 flow rate [kg/h]	860	80
UO_2F_2 equivalent flow rate[a] [kg/h]	753	70
Counter-current H_2O flow rate [kg/h]	100	18
Counter-current H_2 flow rate [Nm^3/h]	18	12
Final product of reactions	U_3O_8	UO_2
Rotational speed [rpm]	2	7
Heat devices temperatures [°C]	750, 900, 900, 780	700, 730, 740, 710, 650, 630

[a] At the entry of the conversion process, UF_6 is instantaneously and completely converted to UO_2F_2 in powder form; the "UO_2F_2 equivalent flow rate" is therefore calculated from the flow rate of UF_6 and the respective molecular masses of UF_6 and of UO_2F_2.

2006), lime and pigments (titanium dioxide calcination) and in extractive metallurgy for the reduction of ore (Boateng, 2008). Rotary kilns are well suited for the conversion of coal and coke (Lebas et al., 1995), for drying (Shahhosseini et al., 2000), for the pyrolysis of solid waste (Descoins et al., 2005; Marias et al., 2005), and are also used for several conversions in the manufacture of nuclear fuel (Debacq, 2001; Thammavong et al., 2011).

Rotary kilns used for the conversion of enriched or depleted uranium are equipped with lifters and are externally and electrically heated, but they differ in size and nominal operating conditions, as can be seen in Table 1: the type of rotary kiln used for depleted uranium conversion is henceforth named "kiln #1"; the type of conversion kiln used for enriched uranium is named "kiln #2". In these rotary kilns, uranyl difluoride (UO_2F_2) is converted into uranium oxides: U_3O_8 in the case of depleted uranium in kiln #1; UO_2 in the case of enriched uranium in kiln #2 (U_3O_8 is an intermediate during the conversion from UO_2F_2 to UO_2).

In this type of rotary kilns, heat and mass transfer are strongly governed by hydrodynamics, which determines—among other characteristics—the quality and duration of gas/solid contact. In order to correctly model the operation of the conversion kilns, it is essential to be able to calculate precisely the solid distribution at any point in the rotary kiln.

While there is an abundant literature on the hydrodynamics of unflighted rotary kilns (see for example Henein et al., 1983; Mellmann, 2001), only a few studies concern flighted rotary kilns (see for example Van Puyvelde, 2009). The hydrodynamics can be studied globally: the effect of lifters on the total hold-up (see for example Friedman and Marshall, 1949), the time of passage (see for example Prutton et al., 1942), or the mean residence time (see for example Britton et al., 2006). A few studies propose calculation of the amount of powder falling through the gas (sometimes called airborne solid), usually in rotary dryers fitted with a large number of lifters (often a dozen, and in some cases several dozen), in which this amount is high. In such cases, it is not worth taking into account the variation of the bulk depth at the bottom of the rotary kiln with the axial position, and the calculated length of particle fall depends solely on the angular position (see for example Fernandes et al., 2009). Moreover, the total flighted powder fraction is mostly not calculated since, in the case of drying with hot gas circulating through the rotary kiln, the solid in the flights plays practically no role in the drying and heating processes. Thus, in these studies, only airborne (and sometimes dense phase hold-up) is quantified (Schofield and Glikin, 1962; Matchett and Baker, 1987, 1988; Sherritt et al. 1993, 1994; Wang et al., 1995; Ajayi and Sheehan, 2012a, 2012b).

In the rotary kilns studied here, the number of lifters is much lower than in dryers (4 or 6 depending on the type of conversion kiln). A substantial amount of solid may therefore remain in the bulk; the quantity of powder falling through the gas is extremely small (although it plays a very important role in the chemical reaction) and the solid in the lifters is likely to react and to play a role in the thermal exchanges with the wall which is externally heated. It has therefore been necessary to develop a novel model to quantify the various amounts of solid.

In a previous study (Debacq et al., 2013), the discharge law of cohesive powders in flighted rotary kilns was obtained both experimentally and theoretically (i.e. from geometrical considerations), including high temperature measurements. Sunkara et al. (2013a, 2013b) published a similar method for the calculation of the discharge characteristics of rectangular flights, but with experiments on non-cohesive particles and at room temperature.

In the present study a model is proposed to calculate the transverse solid distribution in a flighted rotary kiln; this model takes into account the change in the bulk density and therefore in the volumetric flow rate of the solid induced by the chemical reactions. The transverse solid distribution can be calculated by applying the lifter discharge law: for each axial position in the conversion kiln, a 'snapshot' can be determined, representative of the powder fraction η_F in the lifters, the powder fraction η_G falling through the gas and the powder fraction η_B in the bulk (Graphical abstract). This is particularly useful to study mass transfer between these different powder fractions and gaseous reagents. This 'snapshot' also makes it possible to calculate all the thermal transfer areas, such as the area between solid and wall or between solid and gas, etc.

2. Hydrodynamic model

2.1. Axial profile of bed depth

The axial profile of the bed depth (h versus x) was calculated using laws available in the literature: the bed depth at different axial positions along rotary kilns without inserts in rolling mode can be calculated from the differential Eq. (1), proposed by Saeman (1951), Vàhl and Kingma (1952) and Kramers and Croockewit (1952):

$$\frac{dh}{dx} = \frac{\tan\alpha}{\cos\theta} - \frac{3Q_v \tan\theta}{4\pi\omega R^3}\left[\frac{2h}{R} - \left(\frac{h}{R}\right)^2\right]^{-3/2} \quad (1)$$

From observations made in the pilot plant described previously (Thammavong et al., 2011), the presence of a small number of lifters does not modify the shape of the bed depth profile proposed by Saeman.

As suggested by Afacan and Masliyah (1990), the numerical solution of the differential Eq. (1) can be found using a fourth-order Runge–Kutta method. These authors also suggested using a bed depth equal to the height of a lifter plus twice the diameter of the particles ($h_p + 2d_p$) as the boundary condition at the cylinder exit. More recently Specht et al. (2010) found in smooth rotary kilns (without lifters or dam) that the solid depth at the discharge is several times higher than the particle diameter (and not only twice as high, as suggested by Afacan and Masliyah (1990)). Since the particles studied here are very small (Table 2), their size is negligible compared to the height of a lifter (Table 1); after