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Effect of lifter shape and operating parameters on the flow of materials in a pilot rotary kiln: Part III. Up-scaling considerations and segregation analysis

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ABSTRACT

Up-scaling tracer experiments were carried out in a pilot-scale rotary kiln twice as big as the kiln used in the first two Parts of this study. Internal fixtures such as grid, or lifter structure arranged in 3 and 6 rows of single through-out lifters were used. The effects of these removable fixtures and other usual operating conditions, namely, mass flow rate of granular biomass materials, rotational speed and slope of the kiln on the residence time distribution (RTD), the mean and variance of residence time (MRT and VRT), the hold-up (HU), the Peclet number (*Pe*) and corresponding axial dispersion coefficient (*D*), were investigated. Scaling-up rules were derived for the MRT, HU volume fraction and *D* from the results of a comprehensive experimental work. Good agreement was found between the experimental data and the calculated values. The wide size distribution of the beech chips used in the present study allows analysis of particle segregation, which may further increase understanding of the flow characteristics of granular materials, notably within flighted rotary kilns. The results show that while significantly increasing the dispersion, ipso facto, enhancing the mixing, the lifters limit the extent of particle segregation.

1. Introduction

Rotary kilns have become over the years among the most commonly used gas-solid reactors in a variety of applications in metallurgical and chemical manufacturing, but also in the waste disposal. They are equally applicable to a wide range of materials ranging from granular solids to sludge and slurry. In the processing of solids, the particle size distribution is only a function of the handling capacity of the feeding system.

The focus of this study, initiated in [1,2], is the characterization of solids transport within flighted rotary kilns. If there have been several studies in that field up-to-date, most of these studies have generally focused on the bare kiln [3–6] to model through empirical or mechanistic correlations some of the main solids transport variables such as the hold-up, mean residence time or the bed depth profile. A few studies have characterized effect of the lifters on the flow of solids particles [7–11].

The correlations developed by Hwan [12] for horizontal flighted rotary kilns can be mentioned. They are based on dimensional analysis similar to the correlation by Chatterjee et al. [13], which was adjusted using residence time distribution (RTD) measurements conducted in an inclined rotary kiln without lifters but equipped with an exit dam. Hwan [12] performed systematic experiments carried out in horizontal rotary kilns of different length-to-diameter ratios (between 5 and 10), using segmented lifters and different solid materials. From these results, the following equations were established respectively for the prediction of the volumetric filling degree, *f*, the time of passage, τ, and the axial dispersion coefficient, *D*:

$$f = 10.91\theta^{1.14}\left(\frac{d_p}{D_i}\right)^{-0.15}\left(\frac{\rho\omega D_i^2}{\dot{M}/D_i}\right)^{-0.90}\left(\frac{\omega^2 D_i}{g}\right)^{-0.03}\left(\frac{h_l}{D_i}\right)^{-0.52}\left(\frac{L}{D_i}\right)^{-0.40} \quad (1)$$

$$\tau = 8.57\frac{\rho L D_i^2}{\dot{M}}\theta^{1.14}\left(\frac{d_p}{D_i}\right)^{-0.15}\left(\frac{\rho\omega D_i^2}{\dot{M}/D_i}\right)^{-0.90}\left(\frac{\omega^2 D_i}{g}\right)^{-0.03}\left(\frac{h_l}{D_i}\right)^{-0.52}\left(\frac{L}{D_i}\right)^{-0.40} \quad (2)$$

$$D^2 = 0.12\frac{\dot{M}}{\rho u}\theta^{-1.14}\left(\frac{d_p}{D_i}\right)^{0.15}\left(\frac{\rho\omega D_i^2}{\frac{\dot{M}}{D_i}}\right)^{0.90}\left(\frac{\omega^2 D_i}{g}\right)^{0.03}\left(\frac{h_l}{D_i}\right)^{0.52}\left(\frac{L}{D_i}\right)^{0.40} \quad (3)$$

where θ is the angle of repose, d_p is the particle mean diameter, ω is the angular speed, h_l is the lifter height, and u is the axial solids velocity.

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Unsurprisingly these models suggest that the three solids transport coefficients $f, \frac{\tau \dot{M}}{\rho L D^2}$, and $\frac{\dot{M}}{\rho u D^2}$ are dependent of same parameters, however, in the present case they may vary exactly in the same way for the identified set of dimensionless groups, only differing by a multiplication factor.

To further understanding of the flow of materials in inclined flighted rotary kiln units started in Parts I and II, in the present work, granular materials (biomass) of wider size distribution, and a rotary kiln of larger scale were used. As will be presented in the following sections, the present study aims at investigating the effects of lifter shape and configurations, kiln rotational speed and slope, and mass flow rate on:

- the RTD of solid particles, determined from experimental stimulus response test; and the corresponding mean and variance of residence time (MRT and VRT);
- the hold-up (HU) of solid particles;
- the Peclet number (*Pe*) as well as the corresponding axial dispersion coefficient (*D*);
- the segregation of solid particles.

A set of models are proposed for the prediction of the MRT, HU (volume fraction) and *D*. These models, established on the basis of dimensional considerations, can be used either for design or control purposes.

2. Materials and methods

2.1. Apparatus and materials

The pilot scale rotary kiln considered to carry out this study consists of a tube made of an nickel-chromium alloy. The tube, supported on rollers, is 4.2 m in length and 0.21 m in diameter. It can be tilted from 0° and downward to an angle of 7°. The kiln tube can be rotated between 0.5 and 21 rpm through chains and sprockets coupled to a variable speed motor. At the upper end of the tube, the feeding system comprising a 30 L hopper and a vibrating cylindrical conveyor is set up. At the lower end, it is possible to install (in a sealed manner, if necessary) a tank (30 L) for storage. Notice that the feed rate is adjusted by regulating the vibration frequency of the conveyor on the basis of continuous weight measurements of the feeding system by an electronic balance. A second electronic balance is installed at the kiln end, so that both inlet and outlet mass flow rates can be continuously determined.

The smooth inner wall of the kiln tube can be equipped with a grid or a lifter structure. These features are illustrated in Fig. 1. The grid consists of 16 rows of thin rods (5 mm in diameter) equally distributed in the periphery as shown in Fig. 1a. The lifter structure can hold, depending on the desired configuration, a maximum of 36 one-section lifters (30 mm), referred to as straight lifters (SL). The lifters can be longitudinally arranged in a maximum of six rows equally distributed in the periphery: either as single throughout lifters or segmented lifters. The configurations used in this study are represented in Fig. 1b: 3 and 6 rows of single throughout lifters. The main characteristics of the rotary kiln and the order of magnitude of operating conditions investigated in the present work are summarized in Table 1.

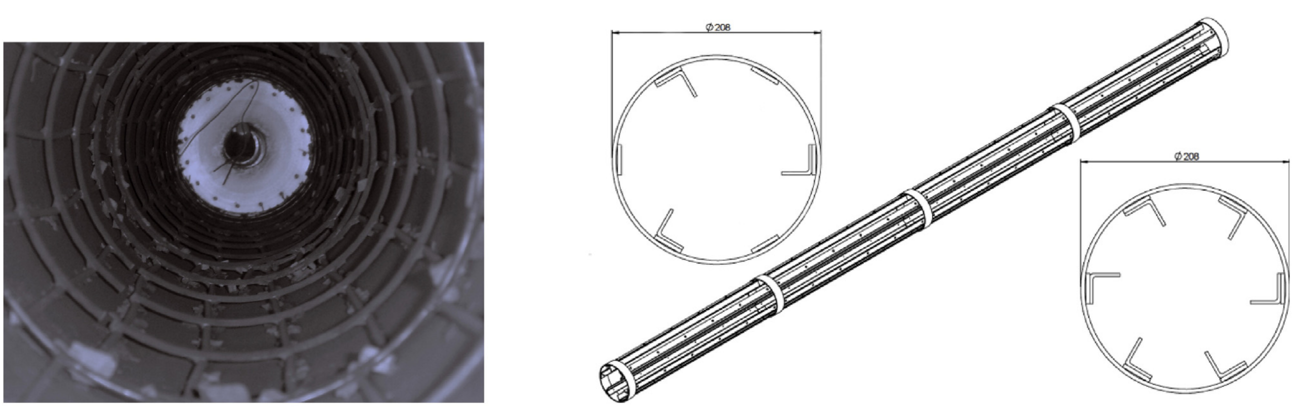
Biomass materials are selected to run the experiments; specifically, beech chips originally from the Picardie forest (France) and supplied by the SPPS (Société de Participation Parisienne des Sciures), are used. A characterization of the size distribution of these particles is manually achieved using a sliding caliper to measure the length, the width and the thickness of 250 particles randomly chosen among tracer particles, which are used for the RTD experiments. The size distribution of these free flowing parallelepiped chips is quite wide as illustrated in Fig. 2: 5–17 mm in length, 2–8 mm in width and 1–4 mm in thickness. In addition, as shown in Table 2, the materials used are characterized by a bulk density, ρ_{bulk}, about 260 ± 30 $kg \cdot m^{-3}$ and a repose angle, θ, about 42 ± 1° measured through the fixed cone method [14].

A comparison with the rotary kiln used in [1,2] shows that the two pilot-scale rotary kilns share a very similar length-to-diameter ratio. However, looking at their dimension ratio, there is a factor about two. The particles size used in the present study is an order of magnitude higher and of a wider distribution compared to those of the sand (0.55 mm) and broken rice (3.8 mm × 1.9 mm) particles used in the first Parts [1,2].

2.2. Experimental procedure

The experiments conducted in the present study were performed at ambient temperature and atmospheric pressure. The RTD measurement procedure was kept as close as possible to the one presented in Bongo Njeng et al. [1]. However, the feeding systems of these units being different, the impulse injection was carried out differently. In order to characterize the flow of beech chips, stimulus response tests are performed using dyed beech chip tracers as emphasized above, following the procedure outlined below:

Step 1: The desired internal fixture is installed at the inner wall, if necessary. The kiln tube is then tilted to the desired angle value. Then the rotational speed and mass flow rate are indicated on the user interface of the operating unit. The rotary kiln is then started and the feed hopper regularly filled with biomass materials to keep it topped up, when needed.



(a) Grid, 16 rows. (b) Lifter structure and configurations: 3 rows of SL (left side) and 6 rows of SL (right side).

Fig. 1. Kiln internal fixtures: a) lifter structure and b) grid.