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Effect of lifter shape and operating parameters on the flow of materials in a pilot rotary kiln: Part II. Experimental hold-up and mean residence time modeling

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ABSTRACT

Experiments were carried out on a pilot scale rotary kiln equipped with lifters at room temperature to investigate the effects of the kiln slope, rotational speed, mass flow rate of materials, and exit dam height on the hold-up and the mean residence time (MRT). The MRT was determined from the residence time distribution measurements as detailed in Part I of this work. Two granular solids having different properties were used: sand and broken rice. Furthermore, two shapes of lifters were compared to determine the influence of lifter geometry: straight lifters (SL) and rectangular lifters (RL). A new model to predict the MRT was established by means of a dimensional analysis. The correlation not only gave good agreement with the experimental data from the present study, but also demonstrated good predictive performances when applied to published experimental data of other kilns; the model is applicable for inclined kilns that process materials in cascading (tumbling) motion, whether or not equipped with lifters or fitted with dams at the outlet end.

1. Introduction

Rotary kilns are gas–solid reactors widely used in mineral process applications and other processes applied to specific granular materials. Due to their extensive use in industry, there have been several studies aimed at modeling the transport of the solids through the kiln cylinder [1–13], which is usually equipped with lifters [14–17]. Most of these studies attempted to understand and predict key parameters such as the hold-up, the mean residence time (MRT) or, as shown in Part I of this study [18], the residence time distribution of solid particles.

Most of the substantial earlier body of scientific literature that exists in the field assumed no axial dispersion through the kiln, such that the time of passage τ was analyzed instead of the mean residence time $\bar{t}$. Others simply conflated the two and assumed the mean residence time to be equal to the time of passage. Indeed the time of passage is very easy to determine; it results from the ratio of the weight of the kiln hold-up to the mass flow rate. However, it should not be forgotten that the time of passage might fail to reflect the flow of solids, especially when there is some axial dispersion, which is increased when using lifters.

One of the earliest equations was developed by Sullivan et al. [1] for the calculation of the time of passage of particles in rotary kilns which do not have lifters, as follows:

$$\tau = \frac{1.77L\sqrt{\theta}}{SDN} \times factor \tag{1}$$

where θ is the angle of repose, S is the kiln slope, N is the rotational speed, L and D respectively are the length and internal diameter of the kiln, and *factor* is a parameter accounting for the operating conditions and is equal to one for a simple kiln without obstructions or constrictions.

Chatterjee et al. [5] used a semi-empirical correlation to predict the mean residence time of solid particles. Their model was built on a dimensional analysis taking into account parameters influencing the flow of materials. However, some parameters were missing such as the exit dam height, which did not appear in the list of parameters, though its effect was studied in their experimental matrix. By applying conditions of dimensional homogeneity, they deduced the following correlation:

$$\bar{t} = k\frac{L^3}{F}\left(\frac{\theta}{S}\right)^a\left(\frac{L^3N}{F}\right)^e\left(\frac{L}{D}\right)^{-c} \tag{2}$$

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where F is the volumetric feed rate, k is a constant equal to 0.1026 and exponents $\{a, e, c\}$ are evaluated as $\{1.054, -0.981, -1.1\}$ [6]. It can be noted in this correlation that the effect of the kiln slope and the angle of repose of solid particles are strongly linked.

In the literature, models for the mean residence time or time of passage, developed for kilns both with and without lifters, range from relatively simple empirical equations to fully mechanistic models. However, we will focus here on some of the simple empirical models developed for kilns equipped with lifters, since the so-called mechanistic models are not suitable for control purposes [4].

Among the earliest models developed for rotary kilns equipped with lifters is the relation of Prutton et al. [2] to predict the time of passage:

$$\tau = \frac{kL}{SDN} + mV_f \tag{3}$$

where V_f is the volume of solids inside a lifter, k is a constant depending on the number and shape of lifters, and m is a constant depending on the gas flow direction and the properties of the materials. This model does not consider the effect of any changes in the flow rate of the solid particles and/or gas through the rotary kiln. Moreover the constants k and m must be determined by fitting the model to experimental data from the rotary kiln in use, thus making the model impossible to use for design purposes.

Certainly the most commonly used model, is the correlation of Friedman and Marshall [19], which is derived from the model of Sullivan et al. [1] with an additional term to allow for air drag on the solid particles. The Friedman and Marshall [19] equation was obtained through the study of hold-up of a range of materials under overloaded conditions:

$$\tau = L\left[\frac{0.3344}{SDN^{0.9}} \pm \frac{0.6085G}{d_p^{0.5}F}\right] \tag{4}$$

where d_p is the average particle diameter, and F and G are respectively the feed rate of the solid particles and the flow rate of the gas. The second term in this equation expresses the air drag; thus the negative sign is used for counter-current flow and the positive sign is used for co-current flow. Compared to the model of Sullivan et al. [1], this model may account for variations in solid and gas feed rates. However, by increasing the solid and gas feed rate by proportional amounts, the predicted residence time will remain constant. Furthermore, the geometric features of lifters are not taken into account in this formulation.

Shahhosseini et al. [4] modified the model of Friedman and Marshall [19] in order to better represent the dynamics of the system, the main objective being to determine the hold-up through the use of the retention time of sugar in the rotary kiln. An additional term was introduced to account for changes in the flow rate of the solid particles under zero gas flow rate conditions:

$$\tau = L\left[\frac{8.5}{\tan(S)DN^{0.8}} + \frac{0.41(G+0.14)}{d_p^{0.5}F}\right]. \tag{5}$$

This model attempted to address some of the shortcomings of the Friedman and Marshall [19] model, but still did not consider internal fixtures of the kiln.

Alvarez and Shene [20] presented an empirical relationship for residence time estimation. It was derived from experimental data concerning solid particles of biological and mineral origin. Their correlation requires up to six constants and five other exponents, leading to a total of 11 parameters to be determined:

$$\tau = \frac{\alpha d_p^{0.032}\rho_{bulk}^{0.956}}{NF(\beta S+1)} + \frac{\gamma d_p^{-0.065}\rho_{bulk}^{0.002}}{\delta S+1} - \frac{\epsilon G^{0.5}}{\varepsilon S+1} \tag{6}$$

where ρ_{bulk} is the density of the bulk materials. This formulation allows prediction of residence times even when the kiln is horizontal and may apply to a wide range of solid materials. However, due to the large number of model parameters there might be a need to fit the model with the system experimental data prior to its utilization.

Recently Thibault et al. [21] proposed two empirical models for the prediction of the mean residence time with the use of a dataset of different types of solids. The models consist of three functions as follows:

$$\bar{t} = \rho_p f_1(1/FN) f_2(S) f_3(G). \tag{7}$$

The three functions f_1, f_2 and f_3 account for the influence of the product FN, the slope of the rotary kiln, and the impact of the gas flow rate on the mean residence time. The definition of f_2 and f_3 as first order functions in the models makes it possible to calculate the MRT for horizontal kilns with no gas flow rate. The main difference between the two models proposed is the definition of the function f_1 which can be either a second-order polynomial with the inverse of FN or a simple function with F and N each with an exponent.

This paper is concerned with the study of the effects of usual operating parameters, shape of lifters, and type of materials on the mean residence time of solid particles as well as on the kiln hold-up. A semi-empirical model obtained from dimensional consideration of the mean residence time of solid particles is also presented. Compared to the other published correlations, this new one should be applicable to a wide range of kilns and operating conditions, and could also be useful for design purposes. Therefore this paper will compare the predictions obtained with this model when applied to experimental data from the literature to the corresponding experimental MRT, and will also present the predictions of published models using the present experimental data.

2. Materials and methods

2.1. Apparatus and materials

The apparatus and materials have been described in Part I of this work. Therefore only their main characteristics are given here. The rotary kiln is a 0.101 m diameter and 1.95 m long tube, which can be tilted to a maximum angle of 5°. Its rotational speed can be adjusted by a driven motor between 2 and 12 rpm. The flow rate of the solid particles was adjusted by regulating the rotational speed of a screw feeder. Different dam heights were used as given in Table 1. In order to study the effect of internal flights, 4 straight one-section lifters of 10 mm (inside length), referred to as straight lifters (SL), and 4 two-section lifters of 10 mm (inside length), referred to as rectangular lifters (RL) due to their right angle cross section as shown in Fig. 1, were used.

Quartz sand (average size 0.55 mm) with a narrow distributed size fraction and broken rice (average size 3.8 mm in length, 1.9 mm in diameter) were employed as experimental materials. The physical properties of these materials are listed in Table 2.

Table 1
Details of the circular dams at the kiln outlet end.

Exit dam height [mm]	Open diameter [mm]	Diameter covered [%]	Area covered [%]
0	101.3	0.00	0.00
13.5	74.3	26.67	46.20
23.5	54.3	46.40	71.27
33.5	34.3	66.14	88.54