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A simple step-change method to determine mean residence time in rotary kiln and a predictive model at low inclination

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ABSTRACT

Rotary kilns are widely used for chemical, metallurgical, environmental protection and fossil fuels pyrolysis processes. To react those thermal treatments efficiently for industrial production, it is necessary to study the residence time distribution (RTD) of materials in rotary kilns. In this paper, a simple step-change method is developed to measure the residence time distribution of solid particles in a rotary kiln. Using salts as the tracer and recording the salinity by the conductivity meter, the effluent salinity curves can be converted to E(t) curves, namely the residence time distribution. The influential factors of the mean residence time (MRT) and the residence time distribution such as rotational speed, incline, feed rate and particle size are evaluated and discussed. The experimental results are compared with three different models, namely the Sullivan model, Chatterjee model and Saeman model. The experimental mean residence time results match well with the Sullivan model except at low incline angles. To predict the mean residence time in rotary kilns at low inclination, which has not been studied before, the experiments at low inclination are conducted and predictive model is presented. The calculated values agree well with the experimental results at low inclination.

1. Introduction

Rotary kilns have wide applications in chemical, metallurgical and environmental protection processes such as blending, drying, grinding, calcining, clinkering and solid waste treatments [1–6]. In order to design rotary kilns for industrial use, it is vital to understand the materials' behaviors in rotary kilns [2,5,7–10]. Previous researchers have studied the passage time and the residence time distribution of materials in rotary kilns. Based on these investigations, the rotational speed, incline, feed rate, the ratio of length to diameter (L/D), dynamic angle of response and constrictions were evaluated to influence the residence time distribution in rotary kilns [3,4,7,11–18]. In addition, the effects of bed depth/bed motion on heat transfer and mixing rates in the kilns were also investigated [2,14,19,20].

In recent years, rotary kilns played increasingly significant roles in thermochemical treatments of solid wastes and fossil fuels. For example, rotary kilns are one of the most important systems for municipal wastes pyrolysis since it can treat liquids or solids wastes of different shapes and sizes simultaneously [21]. Additionally, rotary kilns can be used in fossil fuels such as coal and oil sands pyrolysis due to the several advantages compared with fixed reactors including adjustable residence time, continuous operations, well mixing and uniform heating of materials [6,21–23]. With wide applications in the area of thermal treatments, it is necessary to study and optimize the residence time distribution in rotary kilns for successful thermochemical treatments to occur [4,6]. Proper residence time is desired in thermochemical processes since shorter residence times leads to incomplete reactions while longer residence times may vary the pyrolysis products and result in extra energy costs [4]. Consequently, previous researchers explored several methods to determine the mean residence time of materials in rotary kilns.

Sullivan et al. [7] developed a method to determine the passage time by measuring the hold-up M, of the device when the bed in the kilns came to the condition of equilibrium and the discharging speed was constant. The passage time T, was calculated by using Eq. (1), where F was the mass feed rate of the rotary kiln.

$$T = \frac{M}{F} \tag{1}$$

This method was easy to operate while it was based on assuming all the particles had the same passage time in the kilns. However, the residence time of particles through rotary kilns is a distribution [8]. Consequently, Sullivan's method may cause inevitable discrepancies when determining the mean residence time. Additionally, the

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determination of hold-up can be inaccurate due to particles will reside inside the kiln [24].

In order to measure the mean residence time precisely, many researchers applied the stimulus response test to determine the residence time distribution in rotary kilns [1,5,25]. Independent of adopting step change or pulse injection, tracers are expected to share similar physical properties with bulk materials and are easy to be detected even at low concentrations [1,5]. Two types of tracer detection techniques are applied in determining the mean residence time: offline and online detection [1]. Offline tests have been widely used in previous researches. For instance, Sai.et al. [13] introduced coal and sands as the tracers to determine the mean residence time of ilmenite in the rotary kiln. Tracers were separated from samples manually after collecting samples at regular intervals at the discharge end of the kiln and the mean residence time were determined according to the weight of the tracers and ilmenite. Chen et al. [16] used a stopwatch to record the corresponding inlet and outlet time of all tracers and collected tracers in a container within a certain time interval. The mean residence time of solids can be calculated from Eq. (2), where k was the sequence of tracer, t_k was the residence time of the tracer and z was the number of all tracers.

$$\overline{T} = \frac{1}{z}\sum\nolimits_1^z t_k \tag{2}$$

Li et al. [21] labelled every tracer and measured its residence time one by one. The mean residence time was calculated by using Eq. (3).

$$\overline{T} = \sum\nolimits_{i=1}^{I} t_i E(\Delta t_i) \tag{3}$$

where i was the sequence of sampling interval, Δt_i was the interval of the i st sampling interval, and t_i is the retention time of tracers in the ist interval. $E(\Delta t_i)$ was the ratio of the number of tracers in ist sampling interval of the total tracers. Gao et al. [1] calculated the mean residence time by employing a camera to record the tracer particles in every five or ten images at a time interval of 2 s. Different from the offline tests, the online tests directly recorded the optical, thermal, or electrical signals of tracer concentration, consequently, having higher degree of accuracy compared with offline test [1]. Additionally, fast sample acquisition and signal conversion were required in online detections. Wes et al. [2] and Paredes et al. [4] have successfully applied a spectrophotometer to measure tracer concentration to determine the mean residence time of powder in a rotary kiln. However, this method had the limit of particle size, that was more effective and precise for powder than solid particles [24]. Although the online test had a higher degree of accuracy, fewer online methods have been applied in determining the residence time distribution in rotary kilns since it had higher equipment requirements. Consequently, an online stimulus response method, which has low equipment requirements, is required to determine the mean residence time in rotary kilns.

Several models have been empirical formulated to predict the mean residence time in rotary kilns since modeling plays an important part in industrial devices design and constructions. As we all know, the kiln structure has a significant influence on the mean residence time, for example, the existence of discharge dam can prolong the residence time of materials. For rotary kilns without a discharge dam, Sullivan et al. [7] and Chatterjee et al. [26] presented us two different empirical formulas to calculate mean residence time, shown as follows:

$$t_{sullivan} = 1.77\frac{L\sqrt{\theta}}{DV\varphi} \tag{4}$$

$$t_{Chatterjee} = 0.1026\frac{L^3}{F_v}\left(\frac{\theta}{\varphi}\right)^{1.054}\left(\frac{F_v}{L^3V}\right)^{0.981}\left(\frac{L}{D}\right)^{1.1} \tag{5}$$

The former model ignored the influence of feed rate on the residence time. For kilns with a discharge dam, Sullivan et al. [7] introduced two empirical formulas when the uniform depth of solids in the kiln is less than or more than the height of discharge dam, respectively. These models discussed above were obtained from experiments while there were also mathematical models available to calculate the mean residence time [3,18]. Saeman et al. [27] introduced a differential equation to describe the bed depth profiles h(x) in the cylindrical kilns and h (x) can be calculated by solving the differential Eq. (6).

$$\frac{dh}{dx} = \frac{3\,\tan\theta}{4\pi V}F_v\left[R^2-(\mathrm{h}-R)^2\right]^{-1.5}-\frac{\tan\varphi}{\cos\theta} \tag{6}$$

The hold-up M can relate to $h(x)$ by Eq. (7)

$$M = \rho_s\cdot R^2\cdot\int_0^L(\varepsilon_x-\ \sin\varepsilon_x\ \cos\varepsilon_x)dx \tag{7}$$

where ρ_s is the bulk density of materials and ε_x is defined as $\varepsilon_x = \arccos(1-\frac{h(x)}{R})$, then the passage time T can be calculated using Eq. (1).

Nevertheless, previous researchers have found the dropping-off effects at low incline angles may shorten the mean residence time evidently, which may cause discrepancies to predict the mean residence time in rotary kilns. In addition, the prediction of the mean residence time in rotary kilns at low incline angles hasn't been researched. However, some pyrolysis processes in rotary kilns require long residence time to react efficiently, which is likely to happen at low incline angles. Consequently, it is meaningful to predict the mean residence time precisely in rotary kilns at low incline angles.

The aim of this paper is to develop a new online step-changed method, which has low equipment requirements, to determine the mean residence time of solid particles in rotary kilns and to study the influential factors, which are the rotational speed, inclination and particle size range from 1.25–3.75 mm. The experimental results were compared with three models, namely the Sullivan model, Chatterjee model and Saeman model. Furthermore, a predictive model is presented to predict the mean residence time at low inclination. In addition, the effects of feed rate, kiln incline, and rotational speed on the residence time distribution and variance are discussed to have a deep understanding of axial dispersion in rotary kilns.

2. Experimental section

2.1. Materials

Quartz sands were used as test materials. The salts have a purity greater than 98%, were selected as the tracers. Because they shared similar physical properties with quartz sands, namely, they could simulate the motion state of quartz sands well in rotary kilns. Additionally, the salts could be sensitively detected by the conductivity meter when dissolved into water even if the concentration was relatively low. Pure water was used as the solvent because it had a better dissolution to the salts compared to tap water. Additionally, pure water nearly has no foreign irons, allowing for fewer disturbances when determining the salinity.

The quartz sands and salts used in experiments were both sieved to 6–8 mesh (3–3.75 mm) and 10–16 mesh (1.25–2 mm) by a screening machine to guarantee uniform size distribution. Table 1 shows the physical properties of the quartz sands, salts and pure water. The bulk densities, which were calculated by dividing weight by the volume, were determined by means of a calibrated measuring glass. The Hausner's ratio is calculated by tapped density dividing bulk density and the tapped density is determined by the auto tap device. The static angle of response was measured using a fixed funnel. The solids were poured through a funnel to form a cone with diameter of 0.3 m. The height of the cone was measured and the static angle of response was calculated. A method developed by Sullivan et al. [7] was applied to