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The effect of operating conditions on the residence time distribution and axial dispersion coefficient of a cohesive powder in a rotary kiln

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ABSTRACT

While continuous rotary calcination is a widely used thermal treatment in large-scale catalyst manufacturing, the process's heat and mass transfer mechanisms remain a challenge to characterize and to predict. Thus, the goal of this research is to improve fundamental understanding of rotary calcination to aid in the creation of a scientific methodology for process design and scale-up. For successful calcination to occur, the residence time of the particles must exceed the time required for heating and calcination at a set temperature. The optimal residence time therefore depends on both of these competing time scales, each of which is function of feed material properties, kiln geometry and kiln operating conditions. For uniform treatment of the feed, the particles must also exhibit low axial dispersion. In this work, the residence time distribution and axial dispersion coefficient for a dry cohesive fluid cracking catalyst powder were measured in a pilot plant kiln using a tracer study developed by Danckwerts. Results were successfully matched to the Taylor fit of the axial dispersion model and the Sullivan prediction for mean residence time. It was found that an increase in feed rate, kiln incline and rotary speed decreased mean residence time and overall axial dispersion. Such results have been established previously for free-flowing material like millimeter-sized extrudates, but have not been previously reported for the cohesive powders such as the one used in our work. As in free-flowing material, the axial dispersion coefficient was found to vary with kiln conditions. The values of the axial dispersion coefficients were lower for the powder than for free-flowing material, showing a dependency of axial dispersion on material properties as well as bulk flow behavior.

1. Introduction

With applications in a wide range of solids manufacturing processes including blending, drying, and calcining, the rotary kiln has established itself as an essential device in chemical and metallurgical industries (Brook et al., 1991). The device's popularity stems from its apparently simple geometry – the kiln operates by allowing gravity and rotation to move granular material or powder from one end to the other while the particles are heated. This mechanism has improved product quality in both batch and continuous processes (Brook et al., 1991), and researchers have performed analyses of the process as early as the 1920's (Sullivan et al., 1927). Still, the mass and heat transfer mechanisms in rotary kilns remain a challenge to characterize and to predict; developing fundamental understanding of rotary kiln processes will therefore greatly improve their scale-up from laboratory and pilot plant scales to manufacturing scale.

In preparation of chemical catalysts in particular, a better scientific understanding of rotary kilns will improve continuous calcination processes in which the particle bed exchanges heat with a freeboard gas and the kiln wall as it rotates and moves axially along the kiln (Fig. 1).

Successful calcination occurs when the particle residence time exceeds the time required for calcination. The typically long residence time of the material within the kiln favors uniform treatment of particles (Boateng, 2015), but long residence times lead to large material and energy costs. The key to successful and efficient calcination is then to minimize both the residence time and axial dispersion of particles within the kiln and to understand their relationship to the time required for calcination at a set temperature.

Radial and axial mixing are key factors that influence both

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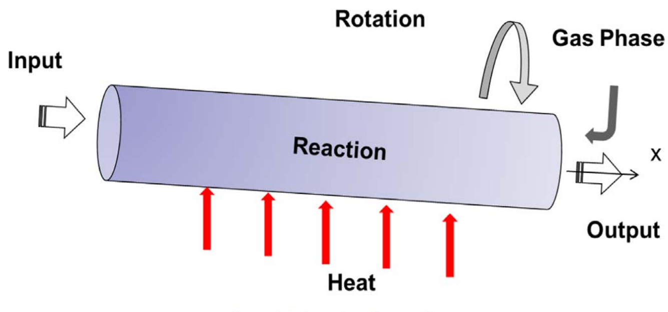

Fig. 1. Schematic of rotary kiln.

residence time and calcination time, and modifications such as lifters (also known as flights or baffles) have been installed in industrial kilns to improve mixing processes by increasing the surface area available for heat transfer (Mujumdar, 2014). The hot gas stream treats the material cascading from the lifters. This mechanism improves heat transfer by increasing the contact time between the gas and the material (Mujumdar, 2014). The hot particles remix with the cooler particle bed, improving heat transfer among the particles and effectively decreasing the time required to treat the material (Mujumdar, 2014; Saeman and Mitchell, 1954). The cascading rate of the lifters and kiln hold up, which is the total amount of materials in the kiln, determine the amount of material exposed to the hot gas flow (Saeman and Mitchell, 1954; Hirosue, 1989; Matchett and Baker, 1987). Several models and experimental studies have been published examining the effect of these lifter designs on heat and mass transfer (Hirosue, 1989; Matchett and Baker, 1987; Sheehan et al., 2005; Sunkara et al., 2013; Lee and Choi, 2013; Njeng et al., 2015a, 2015b, 2016; Sherritt et al., 1993, 1994; Chaudhuri et al., 2006). Many different lifter configurations like rectangular lifters, angular lifters, and circular lifters have been found in industry due to the range of applications employing rotary kilns (Mujumdar, 2014). Numerical simulations conducted by Chaudhuri et al. (2006) found L-shaped lifters to be more effective than rectangular lifters, though both enhance the rate of heat transfer and uniformity of the temperature profile for granular material within the kiln. The uniformity of the bed was found to be directly proportional to the number of lifters used (Chaudhuri et al., 2006). In a recent experimental study for mass transfer, Njeng et al. (2015a, 2015b, 2016) found that the use of lifters slightly increased the mean residence time of the particles. Njeng et al. (2015a) provided a prediction of the axial dispersion coefficient for lifted kilns based off their findings. It was found that the effect of the lifters on the axial dispersion coefficient became more pronounced with an increase in rotation rate and therefore material cascading rate, and slightly higher with increase in incline or smaller flow rate. Lifters also increased the mean residence time of the particles by forcing backflow of the material and minimized the effect of segregation on particle mixing by continuously remixing the particle bed (Njeng et al., 2015b, 2016).

Along with lifter configuration, a material's rheological properties, and the kiln's fill level, kiln incline, and rotation rate influence mixing by determining the mode of motion of the particles within the kiln. Six modes of motion – centrifuging, cataracting, cascading, rolling, slumping, and slipping – are possible (Sullivan et al., 1927). For the rolling mode, Saeman (1951) developed a model to compute the mean residence time based on material properties and kiln geometry. A predictive model for transverse mixing has also been developed by Sai et al. (1990) for particles in rolling mode. In general, these models assume that two layers, the passive and active layers, exist within the particle bed. The passive layer rotates with the kiln wall, and then rolls down the surface of the particle bed in a thin active layer. The time required for the particles to roll down the active layer is very small compared to the time spent in the passive layer.

Based on these studies, the speed of rotation, incline, and feed rate are found to affect the residence time and bed depth significantly. Gao et al. (2013) found that feed rate has little impact on the mean residence time, though Njeng et al. (2015a, 2015b, 2016) found that an increase in mass flow rate showed a decrease in the mean residence time. Studies have also shown that the mean residence time scales with particle aspect ratio and is inversely related to rotary speed and kiln incline (Njeng et al., 2015a, 2015b, 2016; Sherritt et al., 1993, 1994; Gao et al., 2013). While recognizing such trends aid in kiln operation, the mean residence time alone cannot provide insight into the axial dispersion of the particles. For this, the residence time distribution, a probability distribution characterizing the flow profile of a material, must be measured (Sai et al., 1990; Gao et al., 2012, 2011). The width of the distribution depends on material flow determined by inherent properties and operating conditions. Narrower distributions are indicative of yielding a more uniform product and therefore overall less axial dispersion. Previous studies have shown that narrower residence time distributions correspond to high feed rate, high incline, and fast rotation rates (Njeng et al., 2015a, 2015b, 2016; Sherritt et al., 1993, 1994; Gao et al., 2013). The axial dispersion coefficient can be measured experimentally by injecting tracer particles and observing these particles at the outlet using a methodology developed by Danckwerts (1953) to obtain the residence time distribution. Prior experiments have shown that axial dispersion coefficient increases with rotation rate and decrease with an increase in feed rate and kiln incline. In performing a tracer study in a pilot plant kiln operated at room temperature, Gao et al. (2013) found that the axial dispersion coefficient of millimeter-sized particles decreased with rotary speed and incline angle. Higher feed rates and larger angle of repose of the materials led to higher fill levels, reducing axial dispersion. Njeng et al. (2015a, 2015b, 2016) found similar trends in broken rice and sand. These studies were conducted on relatively large particles where the effect of cohesion is negligible (Njeng et al., 2015a, 2015b, 2016; Gao et al., 2013).

For cohesive particles, some studies have reported conflicting results regarding the effect of cohesion on the axial dispersion (Rietema, 1984; Sherritt et al., 2003; Sudah et al., 2002; Gupta et al., 1991; Alexander et al., 2002; Rao et al., 1991; Shinbrot et al., 1999). Experiments by Rutgers, (1965) have shown that cohesive material leads to a higher axial dispersion coefficient, while some simulations and experiments by Sudah et al. (2002) and Gupta et al. (1991) have shown that low degree of cohesion increases mixing, while high cohesion slows mixing. Koynov et al. (2016) measured the axial dispersion coefficient for cohesive powders using Fick's second law in a batch system with and without lifters. Koynov et al. (2016) found that changes in fill level and the presence of baffles did not significantly change the value of the axial dispersion coefficient, but their experimental step up did not allow for correlating the effect of bulk flow with the axial dispersion coefficient.

The aim of the present study is to investigate the effects of operating conditions on the mean residence time and axial dispersion coefficient of dry cohesive powders in rotatory kiln with lifters. The effects of feed rate, kiln incline, and kiln rotation rate on residence time and particle distribution were studied.

2. Materials and methods

2.1. Materials

Zeolitic fluidized cracking catalyst (FCC) powder (W.R. Grace Davison, Columbia, Maryland, USA) was selected as the feed material. This powder was chosen because of its indusrun relevance and to further extend the library of materials used in previous work. Fig. 2 shows the particle size distribution of the FCC powder. The d10, d50, and d90 of the powder are 46, 80, and 140, respectively. Since lifters diminished the effect of segregation by continuously remixing the powder (Njeng et al., 2016), the effects of segregation due to particle