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Discharging granular material from a rotary kiln in a slumping regime: Theoretical and experimental studies

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ABSTRACT

This study developed a theoretical approach to understanding how a set amount of a granular bed is discharged from a tilted rotary kiln (an empty cylinder) once its particle size distribution (PSD) is known and slumping motion occurs. The basis of the study is that the preparation of material for thermal treatment inside a rotary kiln (pyrolysis, gasification, and/or combustion) involves shredding to a desired particle size. Further mechanical stress results from the feeder screws moving material from storage toward the reactor. The most common PSDs found in uniform size reduction processes and mechanical stresses are Gaussian, log-normal, and Rosin–Rammler, of which the latter best fits the PSD in our study. Different particle diameters in the distribution result in an axial segregation when a slumping motion occurs, resulting in particles of different diameters leaving the kiln at different instants. After developing the model, the theoretical data showed good agreement when compared with experimental results obtained from downloading previously shredded carbonaceous material from a rotary kiln at 2 and 4 rpm rotational speeds. The mean residence times at steady state were determined for both rotational speeds and showed good agreement with data provided in the literature.

Introduction

Nowadays, heat treatments such as pyrolysis, gasification, and combustion of waste and biomass represent a valid solution for recovering materials. This includes the production of adsorbents for the removal of pollutants from water (Molino et al., 2013), the production of activated carbon with a high porosity and therefore surface activity (Ariyadejwanich, Tanthapanichakoon, Nakagawa, Mukai, & Tamon, 2003; Gonzàlez et al., 2006; Mui, Ko, & McKay, 2004), and the production of silicon carbide (Galvagno et al., 2007), either for the production of energy to be used on site (combustion) or as a gas energetic carrier that is more flexible (Donatelli, Iovane, & Molino, 2010). These present numerous advantages and possibilities for use in high-efficiency generation systems based on fuel cells or turbines (Kivisaari et al., 2004).

Typically, a thermal treatment plant consists of a reactor, a gas cleaning system, and an energy recovery system. Reactors can be basically classified as fixed bed, fluidized bed, rotary kiln, or entrained bed. Of these, rotary kilns have some advantages such as good mixing capability, flexibility in the treatment of different materials, and efficient heat transfer. Indirectly heated rotary kilns comply well with a number of standard gasifier specifications (Hatzilyberis & Androutsopoulos, 2006), especially for gasifying moist materials (Hatzilyberis, 2011). Because of these advantages, rotary kilns are generally used in industry and a deeper knowledge of the physical and chemical phenomena involved during their operation is desirable and necessary.

For instance, an important aspect is that the time solids take to pass through rotary kilns influences the mass and heat transfer and determines the degree of gas and solid phases in the chemical reaction. Several studies have been undertaken with the aim of determining the mean residence time (MRT) that represents, in steady state conditions, the time range that the feed material uses to pass through and leave the reactor (Li, Chi, Li, Yan, & Cen, 2002; Li, Yan, Li, Chi, & Cen, 2002; Liu & Specht, 2006).

Different features are involved during the rotation of a kiln. First, several types of transverse bed motions can be established, depending on the rotational speed, degree of filling, and frictional properties of the material used (Henein, Brimacombe, & Watkinson, 1985; Mellmann, 2001) as shown in Table 1. In particular, as the

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Nomenclature

g	gravitational acceleration (m/s^2)
n	rotational speed of rotary kiln (rpm)
t	time (min)
D	diameter of rotary kiln (m)
F	mass fraction (wt%)
Fr	Froude number
G	mass flowrate of feeding material (kg/h)
L	length of rotary kiln (m)
M	mass of feeding material (kg)
MRT	mean residence time (min)
Q	volumetric flowrate (m^3/min)
β	slope of rotary kiln (°)
θ	angle of repose (°)
φ	particle diameter (µm)
ω	angular velocity (rpm)

Froude number ($Fr = \omega^2 R/g$, which defines the ratio of a body's inertia to gravitational forces) increases, different conditions follow one another in progression from slipping to centrifuging. The Froude number varies when changes occur in either the rotational speed of the rotary kiln (ω) or the geometry of the reactor (R). Usually, the most desirable bed motion is one that follows a rolling mode, because this promotes good mixing of particles along with rapid surface renewal at the exposed bed, while avoiding centrifuging operation (Boateng & Barr, 1996). This is an important aspect and worthy of attention in designing a rotary kiln.

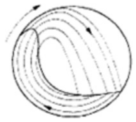
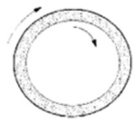
Noting that the rolling mode is the most desirable, many studies have attempted to understand the radial and axial mixing phenomena of bed material during the rotation of a kiln. These include the best condition for heat transfer rate inside the bed, the influence of the diameter of the kiln, loading and wall friction on mixing and crossing the reactor (Bielenberg, Gladysz, & Graham, 2007; Boateng & Barr, 1996; Furuuchi, Ohno, & Gotoh, 1990; Henein et al., 1985; Ingram, Seville, Parker, Fan, & Forster, 2005; Mellmann, 2001; Nakagawa, Altobelli, Caprohan, & Fukushima, 1997; Wightman & Muzzio, 1998). In particular, dealing with axial segregation, evidence shows that bands of alternating largest and smallest particles can form during a rolling bed motion. In many cases, however, the geometry of the kiln does not allow the desirable condition to be established, which is the case for rotary kilns used commonly in research, or when the kiln is filled to a very low level in comparison to values generally adopted (10–40% of entire volume). Often the geometry of the kiln and the impossibility of increasing the rotational speed lead to the establishment of slipping or slumping bed motions. Because these are generally not the type of desired movement, the problem of understanding how particles of different size will dispose themselves in such cases has not been accurately addressed. Few papers have dealt with this phenomenon, particularly the influence of loading, rotational speed, and particle type (Woodle & Munro, 1993). Within this framework, this research aimed to introduce a theoretical approach to predict how a set amount of granular material is discharged from a tilted rotary kiln (an empty cylinder) once its particle size distribution (PSD) is known and a slumping motion occurs. The results expected from the theoretical approach were then compared with experimental data from a bench-scale reactor.

Experimental

Feedstock

The material chosen for the experiments was coal dust purchased from Carbosulcis s.p.a. in Gonnesa (CI), Italy, a company that

Table 1
Transverse bed motion (Mellmann, 2001).

Basic form	Slipping motion		Cascading ("tumbling") motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							
Physical process	Slipping		Mixing			Crushing	Centrifuging
Froude number Fr [−]	$0 < Fr < 10^{-4}$		$10^{-5} < Fr < 10^{-3}$	$10^{-4} < Fr < 10^{-2}$	$10^{-3} < Fr < 10^{-1}$	$0.1 < Fr < 1$	$Fr \geq 1$
Filling degree f [−]	$f < 0.1$	$f > 0.1$	$f < 0.1$	$f > 0.1$		$f > 0.2$	
Wall friction coeff. μ_w [−]	$\mu_w < \mu_{w,c}$	$\mu_w \geq \mu_{w,c}$	$\mu_w > \mu_{w,c}$			$\mu_w > \mu_{w,c}$	
Application	No use		Rotary kilns and reactors; rotary driers and coolers; mixing drums			Ball mills	No use