Powder Technology 292 (2016) 298–306

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Measurement of the axial dispersion coefficient of powders in a rotating cylinder: dependence on bulk flow properties

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ARTICLE INFO

Article history:
Received 11 December 2015
Accepted 27 January 2016
Available online 28 January 2016

Keywords:
Powder flow
Cohesion
Flowability
Mixing
Granular dispersion

ABSTRACT

Rotating drums are encountered in numerous industrial applications, including blenders, rotary calciners, impregnators, coaters, granulators, and cement mixers. In all of these devices, the rotation of the drum is used to engender mixing of the granular material in the radial direction. Axial mixing, because of its significantly lower rate, can also have an impact on the process performance, especially when control of residence time is important. Typically, the particle dynamics in rotating drums are quantified as a function of process conditions, such as rotation speed, fill level, and cylinder size. Particle properties are also important, but previous studies have largely been limited to the effects of particle size. In this work, the quantification of the axial particle dynamics has been expanded to include the effect of bulk flow properties by studying a number of cohesive powders. Fick's second law was found to describe the axial dispersion behavior of cohesive particles. Therefore, changes in behavior can be characterized using the axial dispersion coefficient. The effect of material flow properties was found to be statistically significant; the flowability of the material (as measured using bulk flow properties) correlated significantly to the axial dispersion coefficient. Partial least squares was used to determine that 95% of the variation observed in the axial dispersion coefficient measurement can be explained using particle size, compressibility, and shear cell measurements.

1. Introduction

Predicting the flow behavior of powders and granular materials in a solids processing operation is difficult [1]. To date, a general, theoretical approach describing powder flow, mixing, and segregation has yet to be developed [2]. As a result, the results of numerous experimental measurements and empirical correlations are used to characterize the flow behavior of powders and granular material in specific geometries [3]. These results are often used as the basis for the design and scale-up of manufacturing processes. [4,5] This approach is utilized across industries for many unit operations; e.g. agitated drying, fluidized bed coating, and blending in pharmaceutical manufacturing [6–11] and impregnation, drying, mulling, and calcinations in catalyst manufacturing [12,13]. Many characterization techniques exist to attempt to describe the flow behavior of a powder in a processing step, each technique characterizes the powder flow behavior differently [14]. In addition, each unit operation presents a unique processing environment exposing the material to various levels of stress, altering the flowability of the material [15]. Despite these differences, which often lead practitioners to develop internal characterization standards, the different powder flow characterization methods can be highly collinear [16], which in turns lead to superfluous or redundant measurements. Therefore, the selection of the most useful technique(s) for a given process is often unclear and complex [17].

The horizontal rotating drum is commonly used for processing powders. It appears across industries and processes as rotary kilns, impregnators, cement mixers, coaters, blenders, etc. [18,19] For batch operations, the drum or cylinder is placed in a horizontal position and rotated about its axis. For continuous operations the drum is often arranged in an inclined configuration, typically by a few degrees [20]. There are two main observations that have informed studies of axial mixing of powders and granular materials: that Fick's second law can be used to describe the axial dispersive mixing [21], and that the axial dispersion coefficient can be related to the residence time distribution via the Peclet number, known as the Taylor dispersion model [22–24]. As a result, characterization of the axial dispersion coefficient in batch systems can be related to that in continuous flow systems. These observations have been utilized by many authors to study horizontal rotating drums. Rotary kilns have been the focus of many recent studies [25–29] as have continuous blenders [30–33].

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http://dx.doi.org/10.1016/j.powtec.2016.01.039
0032-5910/

The axial dispersion coefficient has been measured in rotating drums to characterize axial mixing using Fick's second law [34]. Experimentally, tracer particles are introduced and the spatial distribution of the tracer particles throughout the bed is monitored as a function of time, to yield a measurement of the axial dispersion coefficient. Several initial conditions can be used, requiring slightly different mathematical treatment of the results to estimate the dispersion coefficient. Parker et al. [35] used a single particle method, tracking the movements of a single radioactively labeled tracer particle. Publications by Hogg et al. [36], Rao et al. [37], Cahn and Fuerstenau [38], Carley-Macauly and Donald [39], and Wightman and Muzzio [40] described studies where one half of the drum was initially filled with tracer particles. Hogg et al. [41] began experiments with a thin band of tracer particles at one end of the drum and Shoji et al. [42] used a thin band near the center of the drum. Signh [43] started with the tracer particles in a wide band at the center of the drum; this is also the initial condition used in the work reported in this article.

These publications have studied the effect of several process parameters on the axial dispersion coefficient in a rotating drum, including the rotation rate, fill level, and the incline of the drum. In batch systems, it has been found that the axial dispersion coefficient increases with increasing rotational speed [37,44], and an inverse relationship between the fill level and axial dispersion coefficient has been observed; the coefficient decreases with increasing fill level [44]. Abouzeid et al. [45], Hehl et al. [46], and Njeng et al. [47] have studied the effect of process parameters in continuous flow systems and found that the residence time decreases with an increase in rotational speed, drum incline, or feed rate (or, alternatively, an decrease in the fill level).

The effect of particle and bulk flow properties have been considered in several published works. Studies on the effect of particle size report conflicting results [33,37,43,45]. Rutgers found that needle-like particles give lower axial dispersion coefficients than spherical particles [44]. Rao et al. [37] found that increasing surface roughness results in larger coefficients. The ratio of particle–particle friction to particle-wall friction was related to the mixing time by Woodle and Munro [48]. In mixing in high dilution systems with a tracer different from the bulk material, Orr and Shotten found that the ability to mix is dependent on the tensile strength of the bulk material [49]. There have also been equations developed based on continuous flow experiments that relate the axial dispersion coefficient to the angle of repose and the bulk density [50,51]. However, these equations predict an axial dispersion coefficient of zero in “no-net-flow”, i.e. batch, systems; which is contrary to experimental observations. However, as of yet, there has not been a systematic study on the effect of cohesive forces, as characterized by bulk properties, on the axial dispersion coefficient.

This paper examines the effect of bulk flow properties on axial mixing. The axial dispersion coefficient was measured for five materials with a range of bulk flow properties. The rest of the paper is organized as follows. The materials characterized and the experimental method used to measure the axial dispersion coefficient are described in Section 2. Results and discussion are presented for the axial dispersion coefficient as a function of flow properties (Section 3). The discussion of results includes the use of statistical analysis to determine the statistical significance of the material type. It was found that the material type was statistically significant. Using partial least squares regression, it was also found that, for the materials studied here, the variation in the axial dispersion coefficient can be mostly explained by measurements from three flow property characterization methods: particle size, compressibility, and the shear cell. Conclusions are presented in Section 4.

2. Materials and methods

2.1. Materials

The axial dispersion coefficient of five powders was measured: Lactose Monohydrate N.F. Regular (Forremost, Rothschild, WI, USA), Vivapur 102 (JRS Pharma, Rosenburg, Germany), Compap L APAP (Mallinckrodt, Greensville, IL, USA), Zeolite Y (Zeolyst International, Conshohocken, PA, USA), and fluidized cracking catalyst (W.R. Grace & Co., Columbia, MD, USA). These powders were chosen as they are industrially relevant and represent a wide range in flow behavior. The materials and their properties are listed in Table 1. The particle size distribution was measured using a Beckman–Coulter LS 13 320 Series Tornado Dry Powder System laser diffraction particle size analyzer (Pasadena, CA, USA). The cohesion, flow function coefficient, compressibility, conditioned bulk density, and permeability were measured using the FT4 powder rheometer (Freeman Technology, Tewkesbury, Gloucestershire, UK). The FT4 methods are described in detail by Freeman [52,53]. The cohesion and flow function coefficient were measured using the shear cell at an initial consolidation stress of 3 kPa. The compressibility (percent volume change upon compression) and permeability (in terms of pressure drop) were measured using the vented piston at an applied normal stress of 15 kPa, as is typical for these characterization techniques. The flow index was measured using a gravitational displacement rheometer (GDR) as detailed by Alexander et al. [54] and Faqih et al. [55–57]. A smooth acrylic cylinder was used for each material, except for the fluidized cracking catalyst, where a ribbed cylinder was used to mitigate slumping (which is further discussed in Section 3).

2.2. Methods

2.2.1. Visible Light Spectroscopy

This work utilized a tracer material to measure the axial mixing behavior, as is typical of this type of study. In this case, the self-diffusion was of interest and so the material being studied, dyed to a darker color, served as the tracer. The concentration of the dyed material in a sample was measured using a color probe (X-Rite VeriColor Spectro 450, Grand Rapids, MI), i.e. visible light spectroscopy. This method is described in detail by Emady et al. [58]; a brief summary is given here. The surface of a sample with an unknown concentration of dyed material was exposed to light in the visible spectrum. The intensity of the light reflected from the sample surface was proportional to the concentration of dyed material in the sample. Using a calibration curve, the concentration of dyed material in samples was measured. The calibration curve with error bars (the span of which is less than the span of the data point markers) for lactose monohydrate is shown in Fig. 1. The experimental points were fitted with a 4th order polynomial to obtain the calibration curve. The following equation describes the

Table 1
Particle size and flow properties.

Material	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)	Compressibility @ 15 kPa	Permeability @ 15 kPa	FFC	Flow Index
Zeolite	0.80	3.23	11.51	0.35	4.85	4.50	16.34
FCC	45.95	83.61	139.12	0.02	3.66	10.00	39.77
Compap L APAP	74.29	178.29	316.37	0.05	2.17	7.48	34.93
Vivapur 102	25.64	123.59	198.93	0.13	1.71	8.56	22.70
Lactose monohydrate	10.20	70.07	150.73	0.20	13.07	6.05	56.18