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Research article

Measuring residence time distributions of wood chips in a screw conveyor reactor

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ABSTRACT

In rotating screw conveyors both the average and the distribution of the residence time influence the extent and the uniformity of the transformation. Experimenters have applied two distinct experimental approaches to obtain the residence time distribution of granular solids in longitudinal reactors: 1) measuring the mass flow rate of product at the exit from the reactor in response to a step change (either positive or negative) in the mass flow rate of feedstock into the reactor or 2) measuring the appearance of a tracer in the flow exiting the reactor in response to either a pulse or a step change addition of tracer in the inlet. We found that all three methods reveal residence time distributions that are approximately normal (i.e., symmetrical and bell-shaped), but the distribution estimated from the pulse input of tracer exhibited a long trailing tail that was not detectable in either the positive or negative step changes. Second, we demonstrated that a normal probability plot proved valuable in displaying and analyzing the residence time distribution obtained by the pulse addition of tracer. Finally, we observed that all three methods yielded mean residence times that consistently differed from the nominal values. The positive step change averaged 8% shorter, the pulse addition of tracer averaged 7% longer, and the negative step change averaged 60% longer.

1. Introduction

Rotating screw conveyors are widely used to transport granular solids through heaters, coolers, dryers, torrefiers, gasifiers and other reactors where controlling the residence time of the particulates is important. Since the degree of physical and chemical transformation of the granular solids depends on the residence time in the reactor at the target operating conditions, both the average residence time and the distribution of the residence time influence the extent and the uniformity of the transformation.

In an ideal system, the successive flights of the rotating screw conveyor sweep the solids steadily forward at a rate controlled by the rotation rate and flight length of the screw, allowing computation of the ideal or nominal residence time. However, in real systems some particles evade forward transport by passing through the flight clearance (i.e., the gap between the screw and the shell), stepping backwards to a previous screw blade or flight. If the reactor is sufficiently full, then other particles can cascade backwards over the screw axis (or in the case of axle-less screws, over the screw ribbon) into a previous flight. Both of these non-ideal transport processes result in axial dispersion or longitudinal mixing of the solids, observed residence times that exceed the ideal, and variability of the properties of the reactor product.

Levenspiel and Smith [6] characterized non-ideal transport of fluids in longitudinal reactors using solutions to the advection-diffusion equation, and their approach provides the dominant modeling framework for the analysis of resident time distribution. This framework has been applied to the transport of granular solids in screw conveyors by Nachenius et al. [8] and Waje et al. [10], in twin-screw extruders by Kumar et al. [5], and in rotary drums by Bongo Njeng et al. [3] and Colin et al. [4]. These models characterize the residence time distribution using one set of two alternative pairs of parameters: a) the mean and standard deviation of the residence time or b) the mean longitudinal transport velocity and the longitudinal dispersion coefficient. Both sets of parameters are estimated empirically from observed residence time distributions.

Experimenters have applied two distinct experimental approaches to obtain the residence time distribution of granular solids in longitudinal reactors: 1) measuring the mass flow rate of product at the exit from the reactor in response to a step change (either positive or negative) in the mass flow rate of feedstock into the reactor or 2) measuring the appearance of a tracer in the flow exiting the reactor in response to either a pulse or a step change addition of tracer in the inlet. The first method was employed by Nachenius et al. [8] using a negative step change in the inlet mass flow rate. The second method was

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implemented by Waje et al. [10] adding a pulse of dyed solids to the inlet. Both works estimated the mean and standard deviation of the residence time distribution following the method described by Levenspiel and Smith [6] and Levenspiel [7].

In the negative step change experiments of Nachenius et al. [8] the observed mean residence times were consistently longer than the ideal residence times (i.e., computed from the length, pitch, and rotational frequency of the screw), sometimes by as much as 50%. This discrepancy was statistically well explained by the degree of filling of the reactor, with greater degree of filling strongly associated with increases in the observed mean residence time relative to the ideal.

In contrast, the pulse addition of tracer experiments reported by Waje et al. [10] showed observed mean residence times from 250% to 350% longer than the ideal residence times. Although these large differences were not statistically associated with the degree of filling, the authors ascribed the effect to backflow.

There are three objectives of the analysis presented in this article. First, compare the residence time distributions and their properties obtained by three alternative experimental methods: 1) a pulse input of tracer, 2) a positive step change in the reactor mass input rate, and 3) a negative step change in the reactor mass input rate. Second, compare alternative methods describing the residence time distribution and for estimating the mean and standard deviation of the residence time. And finally, compare the estimated mean residence times to the nominal or ideal residence times.

2. Materials and experimental methods

The feedstock for the experiments described below was chipped and screened Douglas fir tops and branches obtained during normal forest harvesting operations. All material passed through a 3.81 mm (1.5 in.) screen. Since the feedstock for each of the four experiments was obtained from a single well-mixed pile, we collected a single representative sample of feedstock from this pile for measuring the particle size distribution by sieving. The results are presented in Table 1 and show 87% of the particles are between 3.99 and 26.7 mm. The bulk density of the feedstock was 180 kg/m^3 (11 lb/ft^3).

The tracer used in these experiments was the feedstock dyed with red ink. The ink, marketed for refilling inkjet printer cartridges, was sprayed onto the feedstock by hand and air dried. In the reactor, the feedstock was not exposed to substances that would destabilize the ink during the experiment.

All of these experiments were conducted in a torrefier reactor produced by Norris Thermal Technologies (Tippecanoe, Indiana) that incorporates a Spiraoule® electrically heated, shaftless screw conveyor (ETIA, France). During these experiments, the screw conveyor was not heated and the lid for the reactor compartment was removed. Fig. 1 provides a schematic diagram of the part of the torrefier system used here. Feedstock is added to the input hopper and is fed into the torrefier reactor by a 6-chamber, rotary airlock at a rate controlled by the speed setting of motor M1. Each chamber of the airlock has a volume of 273 cm^3. The feedstock is moved through the reactor by the shaftless screw conveyor at a rate controlled by the speed setting of motor M2. The conveyor was 166 cm (65.5 in.) long and had a diameter of 13.3 cm (5.25 in.) with a pitch of 5.08 cm (2.0 in.) and a screw blade width of 4.45 cm (1.75 in.). Material exits the reactor through an output airlock that is identical to the one used at the inlet. The speed setting for motor M3 controls the output rate of the solid product. During normal torrefier operation the screw is heated and syngas is extracted through the syngas outlet.

Table 1
Particle size distribution of feedstock.

Lower size limit (mm)	Upper size limit (mm)	wt (g)	% wt
50.8	–	5.3	1%
38.1	50.8	6.1	1%
26.7	38.1	10.4	2%
18.8	26.7	88.2	14%
13.3	18.8	34.9	6%
11.1	13.3	156.0	25%
7.94	11.1	109.3	18%
5.59	7.94	86.3	14%
3.99	5.59	74.6	12%
2.79	3.99	17.7	3%
1.00	2.79	18.1	3%
0	1.00	16.3	3%
Total		623.2	100%

In each of the four residence time experiments that were conducted, the reactor was initially empty and the motor speeds for the two airlocks and the screw conveyor were fixed at the values presented below in the results and discussion. In order to reduce or avoid backward transport of particles in the reactor due to over-filling, longer residence time runs required reduction of the mass flow rate through the system. Fig. 2 presents the ideal time pattern of the mass flow rate at the inlet of the input air airlock (dotted line) and at the exit from the output airlock (solid line). At time t = 0, feedstock was added to the input hopper and soon began to enter the reactor, beginning the positive step change in the input rate. When the hopper feedstock level became low, additional feedstock was added. When the mass flow rate exiting the output airlock reached steady state (i.e., the average over time became approximately constant and the input and output mass flow rates became equal) and the feedstock hopper became empty, the positive step (rising arm) portion of the experiment was concluded and the pulse of tracer was added, beginning that portion of the experiment. After all the tracer had entered the input airlock, feedstock was again added to the hopper and continued to be added as necessary. When the material exiting the output airlock no longer contained tracer, the hopper was emptied and no additional feedstock entered the reactor, beginning the negative step change in the input rate. When the mass flow rate exiting the output airlock became consistently zero, the experiment was ended.

Mass flow rates were measured at the exit from the output airlock by collecting all of the material exiting the reactor over a measured time interval of either 30 or 60 s. The material was collected in a tared container, the container with material was then weighed on a 0.1 g balance, and the result was recorded. Collected material containing tracer (i.e., labeled feedstock) was transferred to a labeled plastic bag, sealed, and stored for later analysis.

After the conclusion of the experiment, each of the bagged samples containing tracer material was re-weighed and screened through a 0.236 mm (0.093 in.) sieve to eliminate fines to facilitate sorting by hand. The remaining material was then sorted by hand to separate the tracer from the feedstock and then weighed and recorded.

3. Theory and analytical method

The theory and methods described here for estimating the mean and standard deviation of the residence time are based on those originally developed by Levenspiel and Smith [6] and recently applied by Nachenius et al. [8] and Waje et al. [10] to the transport of granular solids by screw conveyors. Two novel variations on these methods are highlighted below (i.e., a graphical and linear regression method using normal probability plots and the use of the median residence time to estimate the mean).

The theoretical or ideal residence time in the screw conveyor (τ_{sc}) can be computed from the length of the conveyor (L), the length of the screw flight or pitch (p), and the screw conveyor (i.e., M2) rotation rate (ω_{sc}) (see Fig. 1):

$$\tau_{sc} = \frac{L}{p\cdot\omega_{sc}} \quad (1)$$

This ideal screw conveyor residence represents the amount of time required for a parcel of feedstock entering the reactor to arrive at the