NUKLEONIKA 2002;47(4):173–176

ORIGINAL PAPER

Radioisotope tracer study in an indirectly heated rotary dryer

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Abstract A radioisotope tracer study was carried-out in a pilot scale indirectly heated rotary dryer to measure residence time distribution (RTD) of sand particles. Lanthanum-140 labeled sand was used as a tracer. Mean residence time (MRT) and variance of the tracer distribution curves were calculated from the measured RTD curves. From the calculated MRTs, solid holdup in the dryer was estimated. The qualitative comparison of the dimensionless variance with the data published in the literature led to the conclusion that the rotary dryer behaves as a plug flow system. The results of the study were used to design a full-scale industrial rotary dryer.

Key words holdup • lanthanum-140 • mean residence time • radioisotope tracer • residence time distribution • rotary dryer • variance

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Received: 17 October 2001, Accepted 15 July 2002

Introduction

Indirectly heated rotary dryers are commonly used for drying, cooling, calcination, etc. of particulate materials in various process industries. Widely varying arrangements exist in these units for the heating surface configuration. Heat transfer surface is commonly provided in the form of concentric rims, one or more in number, located suitably near the inner surface of the drum and running parallel to the drum axis. Cooling/heating medium is circulated through these tubes to effect heat transfer. In view of large lengths of these tubes, intermediate supports are required to be provided. The supports are usually circular baffle plates. These baffle plates pose obstruction to the flow causing axial mixing. In addition to this, the rolling motion along with the baffle plates act as a flow distributor. However, for uniform drying/cooling/calcination and higher conversion, the axial mixing should be minimum and the rotary drum system should behave as a plug flow reactor. The measured residence time distribution (RTD) of process material is used to estimate the degree of axial mixing in industrial process systems. Thus, if one knows the degree of axial mixing, then appropriate steps could be taken to prevent or minimise this axial mixing.

Radioisotope tracers are very effective tool to measure RTD of process material and investigate its transport behavior because of their high detection sensitivity, "in-situ" detection, physicochemical compatibility, wide choice and application in harsh industrial environment [2, 4]. Karra and Fuerstenau [6] measured the RTD of dolomite feed in rotary drums of different diameters using colored dolomite as a tracer and examined the effect of discharge plate geometry on axial dispersion. They used axial dispersion model and moments method to estimate axial dispersion coefficient (*D*)/Peclet number (Pe). Their results showed that axial dispersion increases with increase in discharge plate opening (baffle space) from 3.5 to 6 cm and decreases when baffle space increases from 6 to 8 cm. Thus, the axial dispersion coefficient was minimum (maximum Peclet number) when the discharge baffle space is 6 cm. These studies were used to correlate mixing effects in a grinding mill. Hehl *et al.* [3] investigated the movement of soda in a horizontal drum mounted with a ring-shaped constriction at the outlet using sodium bicarbonate as a tracer. Samples were collected at the outlet and concentration of the sodium bicarbonate was measured from the weight loss due to the thermal decomposition of the sodium bicarbonate into sodium carbonate. They used axial dispersion model and moment method to estimate the values of Pe, which were found to be more than 80 at all the operating conditions. Abouzeid *et al.* [1] used axial dispersion model to develop a scale-up criterion for residence time distribution in rotary drums and used the same to predict RTD under various operating conditions for drums of different dimensions. The predicted RTDs were in agreement with the experimentally measured RTDs. Wes *et al.* [7] measured the RTD of potato starch in industrial scale horizontal rotary drums without baffles and estimated axial dispersion coefficient, *D*.

This paper describes a radioisotope tracer study carried out in a pilot-scale, indirectly heated rotary dryer system with an objective to investigate the effect of internal geometry (heating tubes and baffles) on residence time distribution and axial mixing of solids.

Experimental

The experimental set-up used in the present study is shown in Fig. 1. The rotary dryer consisted of a vibratory feeder and a rotary drum of diameter 0.45 m and 1.9 m long. To simulate the effect of heating tubes, 8 dummy aluminum tubes of diameter 9.5 mm were used. Two four segmented baffles, one at the centre and other at the end were used to support the dummy tubes. Spirals were mounted at the inner surface of the dryer at the inlet for uniform radial distribution of the feed material. The vibratory feeder consists of a rectangular metal pan of about 100 cm length and 40 cm width. The experiments were performed in cold conditions. Silica sand, with particle size distribution ranging from 150–600 microns, was used as the test material. A series of 12 experiments was carried out at selected operating conditions i.e. flow rate, drum speed, baffle space and slope. The flow rate, drum speed and slope varied from 3–15 kg/min, 4–7 RPM and 1–2°, respectively. The spacing between the segments of the baffle at the discharge end was kept constant at 6.0 cm whereas in some of the tracer tests, the centre and end baffle spacing was kept 6.0 and 12.0 cm, respectively.

Sand labeled with radioisotope lanthanum-140 (half-life: 40 h, gamma energies: 0.33–2.54 MeV) was used as a tracer and about 20 MBq activity was used in each tracer test. The sand (about 100 g) was first treated with acid and then washed with distilled water till the acid was removed. The treated sand was agitated in radioactive solution of $LaCl_2$ of known activity for about 15 minutes. The sand was allowed to settle and the solution was decanted. The sand was then dried and used as a tracer. Laboratory tests showed that about 70–80% activity was found to be adsorbed on the sand. The sand labeled with lanthanum-140 contained in a plastic vial was transported to the experimental site in a lead pot of thickness about 4.0 cm. The labeled sand (tracer) was injected manually into the funnel of the dryer as shown in Fig. 1. The injection time of the tracer was about 3–4 s and thus could be considered as an impulse injection (Dirac's Delta function) as the residence time of the feed is much larger than the total mean residence time of the feed. The passage of the tracer along the length of the dryer was monitored at three different axial positions using three independent 2.54×2.54 cm NaI (Tl) scintillation detectors, D_1, D_2 and D_3 (M/s Bicron corporation, U.S.A. made) connected to three ratemeters, R_1, R_2 and R_3. The detectors D_1 and D_2; and detectors D_2 and D_3 were separated by distances 86.5 and 93.5 cm, respectively. Lead collimators of about 2.5 cm thick with a window of 5 cm width and 20 cm length were used to collimate the detectors. It is assumed that the tracer gets homogeneously mixed in the entire thickness i.e. about 10–15 cm of the sand bed. Since the energy of the lanthanum-140 is quite high and thus will be able to penetrate through the sand bed and the wall of the dryer and reach the detector. The threshold levels of the ratemeters were so adjusted that each of the three detectors gives the same radiation counts for a preset time with and without a standard source. The natural background radiation levels registered by the three detectors were recorded (about 20 readings) prior to the injection of tracer and with tracer away from the experimental set-up and the average background radiation level was calculated. After the injection of

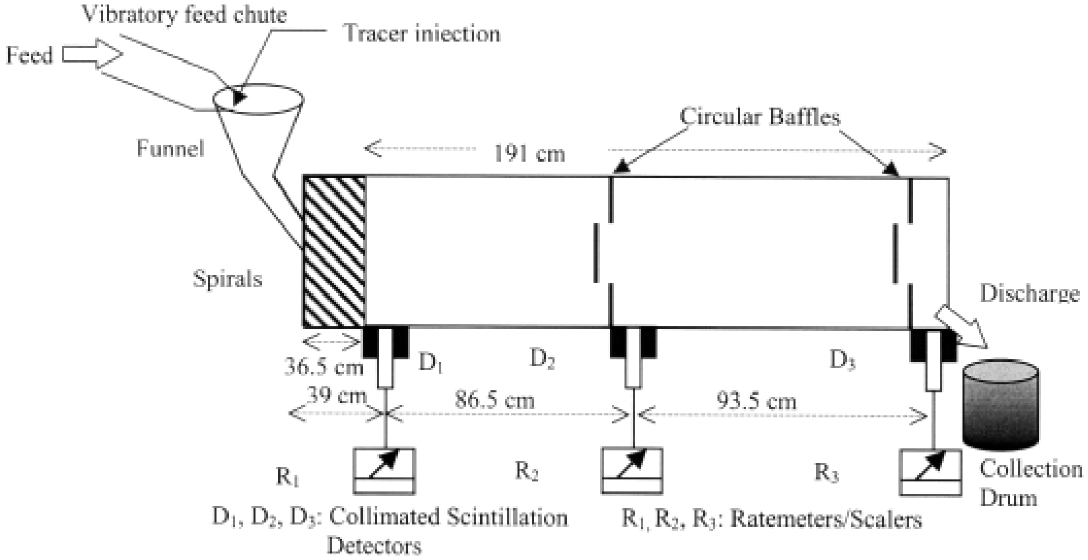

Fig. 1. Schematic diagram of rotary dryer and experimental set-up.

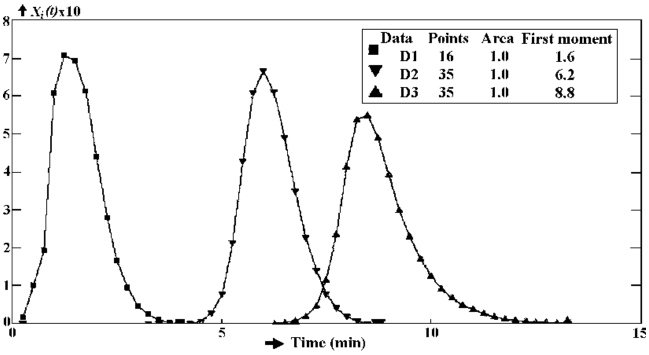

Fig. 2. Normalized tracer concentration distribution curves (Run no. 4).

tracer, the passage of tracer was monitored till the tracer concentration reached the natural background radiation level. The sand contaminated with radioisotope lanthanum-140 was collected in plastic drums and stored in a separate room till the radiation levels in the sand reduced to the natural background level.

Data analysis and results

The measured tracer concentration data were corrected for background and area under each tracer distribution curves recorded by the three detectors (D_1, D_2 and D_3) were estimated. The difference in the area of the three curves was within the experimental error. This implies that the tracer balance was achieved in all the runs. The normalized tracer distribution curves were obtained by dividing each data point by the estimated area of the respective curves. One of the representative plots of treated and normalized tracer distribution curves is shown in Fig. 2. The data treatment procedure and analysis procedure is discussed in detail in the IAEA [5]. First moments (M_i) of the input and the output tracer concentration curves were determined using the following relation:

$$M_i = \frac{\int_0^t t_i C_i(t_i) dt}{\int_0^t t_i C_i(t_i) dt} \tag{1}$$

where $C_i(t)$ is tracer concentration at time t_i. The difference of first moments of the two curves i.e. measured at the inlet and outlet, gives MRT of process material in the system. Thus:

$$\bar{t}\ (\text{MRT}) = M_2 - M_1 \tag{2}$$

where M_1 and M_2 are values of the first moments of inputs and the output curves, respectively. Based on the calculated MRT, the solid holdup (H_s) was calculated using the following relation:

$$H_s = \bar{t} \cdot Q_s \tag{3}$$

where $\bar{t}$: experimentally determined MRT, Q_s: solid flow rate. The spread in the tracer distribution curve $X_i(t)$, is characterized by the variance, $\sigma^2(t)$, and is given as:

$$\sigma_i^2(t) = \int_0^\infty X_i(t)\left(t - \bar{t}_i\right)^2 dt \tag{4}$$

The dimensionless variance is obtained using following relation:

$$\sigma_i^2(\theta) = \frac{\sigma_i^2(t)}{\bar{t}^2} \tag{5}$$

where, θ is dimensiomless time ($\theta = t/\bar{t}$) and $i = 1, 2, 3 ...n$.

Using the above relations, the MRT, solid holdup and variances between the inlet and the outlet detectors (D_1 and D_3) were obtained and are given in Table 1.

Discussion

From the published literature [3, 6] it was already known that the slope of 2° and center and end baffle spacing of 6 cm each were optimum geometrical condition to operate a rotary dryer. Thus the present study was focused to investigate the behavior of the rotary drum at slope of 2° and the baffle spacing of 6 cm each, as a function of solid flow rate and two drum speeds i.e. 4 and 7 rpm. From the measured tracer concentration data, MRT, H_s and $\sigma^2(\theta)$ were estimated between the inlet (D_1) and outlet (D_3) curves (see Table 1). The values of MRT ranges from 3.4 to 15.2 minutes under the entire range of operating conditions. At a constant slope (2°), baffle spacing (6 cm) and drum speed (4 or 7 rpm); the MRT has been found almost linearly decreasing with increasing solid flow rate. The MRTs were found to be higher at lower speed (rpm). Similarly, the solid holdup was found to be linearly increasing

Table 1. Operating conditions and results of radioisotope tracer study.

Run no.	Flow rate (kg/min)	Slope (degree)	Speed (rpm)	Spacing (cm)		$\bar{t}$ (min)	Holdup (kg) $H_s = \bar{t} \cdot Q_s$	$\sigma^2(\theta)$
				centre	end			
1	3.67	2	4	6	6	9.7	35.6	2.40×10^{-3}
2	5.0	2	4	6	6	9.2	46.0	2.65×10^{-3}
3	7.0	2	4	6	6	9.0	63.0	13.98×10^{-3}
4	10.3	2	4	6	6	8.3	85.5	13.25×10^{-3}
5	3.0	2	7	6	6	4.5	13.5	11.07×10^{-3}
6	6.3	2	7	6	6	4.6	29.0	3.83×10^{-3}
7	10.67	2	7	6	6	4.2	45.0	4.95×10^{-3}
8	15.0	2	7	6	6	3.4	51.0	6.75×10^{-3}
9	3.0	1	4	12	6	15.2	45.6	10.4×10^{-3}
10	3.67	1	4	12	6	14.2	52.0	5.50×10^{-3}
11	5.2	2	4	12	6	10.5	55.0	9.98×10^{-3}
12	6.67	2	4	12	6	9.3	62.0	13.62×10^{-3}

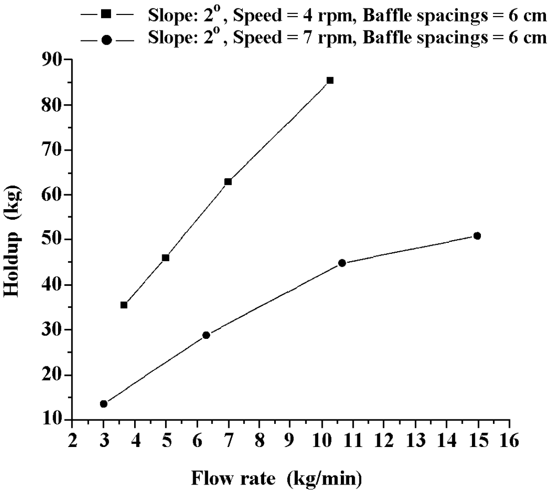

Fig. 3. Variation of solid holdup as a function of a flow rate.

with increasing flow rate at the above-mentioned operating conditions. The solid holdup was found to be higher at lower drum speed. The variation of solid holdup with varying flow rate at two different drum speeds i.e. 4 and 7 rpm is shown in Fig. 3. However, during the study, no attempt was made to directly measure the solid holdup by some other independent means. The trend in MRT and solid holdup with varying flow rate and drum speed, observed in the present study, are in good agreement with the trends reported in the literature [7].

The value of dimensionless variance, $\sigma^2(\theta)$, between the inlet and outlet measuring points is a measure of degree of axial dispersion. The more the value of dimensionless variance, the more will be the degree of axial dispersion. In the present study the values of the dimensionless variance, $\sigma^2(\theta)$, were found to be ranging from 1.0×10^{-3} to 14.0×10^{-3}. However, no definite trend in variance with varying flow rate, was observed. The studies published in the literature were carried out in rotary dryers of different dimensions, with different process material and different design and operating conditions; and therefore only a qualitative comparison was possible to draw the information about the degree of axial mixing. Helh *et al.* [3] found the values of $\sigma^2(\theta)$ to be ranging from 14×10^{-3} – 24×10^{-3} and the axial dispersion coefficient, D, of the order of 2×10^{-4} m^2/min. Similarly, Wes *et al.* [7] found the values of $\sigma^2(\theta)$ and D to be ranging from 10×10^{-3} to 13×10^{-3} and 25×10^{-4} to 60×10^{-4} m^2/min, respectively. Based on the relatively low values of $\sigma^2(\theta)$ (1.0×10^{-3} to 14.0×10^{-3}) obtained in the present study and their comparison with the values published in the literature, it can be qualitatively concluded that the dryer behaves as a plug flow system under the given operating range of parameters. This indicates that the heating tubes and the circular baffles at the center and at the end of the dryer do not cause significant longitudinal mixing. However, the channeling in tracer concentration distribution curves (parallel flow paths) was observed at some of the operating conditions. The channeling may be either because of the improper tracer injection or the presence of spirals at the inlet of the dryer; and not because of the flow behavior of the dryer. Since, the detection geometry in all the tracer tests was identical, the possibility of error in measurement or artifacts being the reason for channeling is ruled out.

Conclusions

The residence time distribution of solids i.e. sand particles have been measured in a pilot scale rotary dryer system using radioisotope tracer technique. The technique with lanthanum-140 labeled sand as a tracer has been found to be an ideal tool to measure RTD of solids in rotary drums. The mean residence times, solid holdup and variances have been estimated from the measured tracer distribution curves. The comparison of the results of the study with the results published in the literature [1, 3, 6, 7], qualitatively led to the conclusion that the rotary dryer behaves as a plug flow system under entire range of operating parameters. The internal geometry of the dryer (heating tubes and baffles) does not significantly affect the plug flow behavior of the dryer. The results of the study could help to choose the optimum operating and design conditions; and help to design a full-scale rotary dryer for industrial use.

Acknowledgments Author is grateful to C. V. Manian and H. P. Dedhia of M/s Larsen and Toubro Ltd., Mumbai for their help in conducting the experiments and S. M. Rao and S. V. Navada for their support during the course of this study.

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