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Thermal bed mixing in rotary drums for different operational parameters

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HIGHLIGHTS

- Mixing of hot and cold particles was evaluated for different rotational speed and filling degree.
- Thermal mixing time decreases with higher rotational speed and lower filling degree.
- The influence of filling degree on thermal mixing time is not significant at high rotational speed.
- Experimental values for low rotational speed are in the range of predicted values of the penetration model by Schlünder and Mollekopf, (1984).

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ABSTRACT

The transversal thermal bed mixing was experimentally investigated in a batch rotary drum with a diameter of 0.6 m and a length of 0.45 m. The drum was filled with two fractions of granular material with different thermal conditions and the mixing temperature in the solid bed was measured with thermocouples located at different bed height. Quartz sand with a mean particle diameter of $d_P = 0.2$ mm was used as test material. The operating parameters, rotational speed and filling degree of the drum were varied in the range of $n = 1$–6 rpm and $F = 10$–20% respectively, whereas the influence on thermal mixing time was evaluated. The thermal mixing behavior was shown in terms of time constant, number of bed rotation, peak time and mixing number. Thermal mixing time decreases with higher rotational speed and lower filling degree. Comparison between experimental data and penetration model shows good agreement for low rotational speeds.

1. Introduction

Rotary drums are widely used in chemical and metallurgical industries for thermal treatment of powder and granular materials. The processes in rotary drums are for example drying of salt, calcination of limestone, sintering of cement, reduction of iron ore, waste incineration and catalyst reactivation. In these processes, the mixing mechanism inside the solid bed dominates the bed homogeneity as poor mixing creates temperature or concentration gradients inside the solid bed. Hence, the mixing is an important criterion for the quality of the final product of the rotary drum process. It depends on many parameters such as operational parameters (rotational speed, filling degree, material throughput, flow rate of gas), design parameters (diameter, length and inclination angle of the drum) and material properties (particle size and shape, density, heat penetration depth). The mixing occurs in both axial and transverse directions, but the transverse mixing is faster than the axial mixing by few orders of magnitude and greater than axial mixing since the bed material moves three to four times in the transverse plane (Nityanand et al., 1986; Boateng and Barr, 1996a). Since the processes in rotary drum involve exchange of heat, mixing in rotary drum not only influences by mechanical mixing, but it also depends on heat transfer between the particles in the solid bed. Hence, the thermal process of a rotary drum is predominantly defined by the coupled amount of transverse particle mixing and heat transport inside the bed.

A lot of works have been done on the mechanical granular mixing in rotary drum. Experimental work was done by using color tracer particles (Wes et al., 1976; Woodle and Munro, 1993; Hogg et al., 1969; Hajra and Khakhar, 2005; Lehmberg et al., 1977;

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Nomenclature

A_{drum}	cross sectional area of rotary drum [m^2]
$A_{solid\ bed}$	cross sectional area of solid bed [m^2]
$c_{p,S}$	heat capacity of solid bed [kJ/kg/K]
d_P	particle diameter [mm]
F	filling degree [%]
Fr	Froude Number [dimensionless]
Fr'	modified Froude Number as in (Kwapinska et al., 2006) [dimensionless]
h	bed height [mm]
k	decay constant [s^{-1}]
n	rotational speed [rpm]
$M(t)$	mixing Index [dimensionless]
N_{bed}	number of bed revolution [dimensionless]
N_{mix}	mixing number [dimensionless]
R	drum radius [mm]
T	temperature [°C]
t	time [s]
t_{mix}	mixing time [s]
t_{peak}	time between two peaks [s]
ΔT_0	initial temperature difference (t=0 s) [K]
$\Delta T(t)$	temperature difference at time, t [K]
ΔT_∞	equilibrium temperature difference ($t=\infty$)
ε	filling angle [rad]
Θ	dynamic angle of repose [deg]
λ_S	effective thermal conductivity of the solid bed [W/m/K]
ρ_S	bed density [g/cm^3]
τ	time constant [s]

Hogg and Fuerstenau, 1972; Van Puyvelde et al., 1999; Schutyser et al., 2001; Liu et al., 2015), the radioactive particle tracking (RPT) method (Alizadeh et al., 2013) and magnetic resonance imaging (MRI) (Kawaguchi et al., 2006). Experimental investigation on the transverse mixing was done by Lehmberg et al. Lehmberg et al., (1977) in a laboratory drum reactor (L=300 mm and D =310 mm) using colored and hot tracer particles. By using color tracer particles, it was demonstrated that the mechanical transverse mixing increases with higher rotational speed, similar to the result by Wes et al. Wes et al., (1976). The experiments using hot tracer particles were described by the exponential relation as a function of time and time constant. However, in this work the temperature of the bulk was only measured near to the upper edge of the bed surface.

Liu et al. Liu et al., (2015) investigated the mixing in a rotary drum using variance and contact methods. The transverse mixing was captured by a video camera and RGB color analysis was performed. A dimensionless mixing index, $M(t)$ was used to describe the mixing quality. The degree of particle mixing was determined by using first order and second order regression models. Based on the experimental observation of Schutyser et al. Schutyser et al., (2001), complete mixing is achieved when the entropy of mixing reaches 0.9. Therefore, the mixture was considered well mixed when the mixing index, $M(t)$ was greater than 0.9 (Schutyser et al., 2001, 2002; Gosselin et al., 2008; Aissa et al., 2010; Sulaymon et al., 2010). From the results, the second order regression model showed a better fit than the first order model.

Several efforts have been made to model (Boateng and Barr, 1996b; Van Puyvelde et al., 2000) and simulate transverse mechanical mixing in rotary drum. Different simulation method such as dynamic simulation (Puyvelde, 2006), discrete particle simulation (DPS) (Schutyser et al., 2001, 2002) and the discrete element method (DEM) (Finnie et al., 2005; Kwapinska et al., 2006) were used. Longitudinal and transverse mixing were investigated by Finnie et al. (2005) using a DEM approach for various rotational speeds and filling degrees. The transverse mixing was characterized by entropy-like mixing index. The influence of filling degree and rotational speed on mixing speed was determined. With same number of drum revolutions, the mixing speed is increased with lower rotational speed and filling degree. Furthermore, the transverse mixing of particles in a rotary drum was investigated by Kwapinska et al. Kwapinska et al. (2006) using 2-D DEM. The simulations were done with various rotational speeds, drum diameter, filling degree and mean particle size. A modified rotational speed was given by including the wall coverage angle (filling angle). A comparison of simulation results with the experimental data by Van Puyvelde et al. (1999, 2000) showed good agreement. These results were compared in terms of mixing time and mixing number. The mixing times were increased with higher filling degree, smaller particle size, lower rotational speed and bigger drum diameter.

Furthermore, thermal mixing (coupled of mixing and heat transfer) in a rotary drum was investigated using hot tracer particles (Lehmberg et al., 1977; Kröger et al., 1979), DEM approaches (Chaudhuri et al., 2006; Xie and Feng, 2013; Gui et al., 2013), coupled DEM with computational fluid dynamics (CFD) (Shi et al., 2008) and thermal particle dynamics (TPD) (Figueroa et al., 2010). Experiments on thermal mixing were done by Kröger et al. (1979) by extending the work of Hehl et al. (1978). The mixing of hot and cold particles of soda was conducted in a laboratory rotary drum with diameter of 250 mm and length of 600 mm. The results showed that as the rotational speeds increase, the mixing intensity increases which represented by the decreasing of time to half-value. However, as the temperature was measured at one location near the surface of the bulk, the temperature fluctuation for the total bed height could not be measured.

Schlünder (1984) and Schlünder and Mollekopf (1984) developed a penetration model to describe the cooling, drying or heating process of an agitated bed by the wall. The continuous mixing process was discretized to a sequence of static period, where the static period ends at time, $t_R=N_{mix}/n$ with N_{mix} as the number of revolutions needed to achieve perfect mixing. It depends on Froude number and kind of mixing apparatus. The estimation of mixing number using these equations is only coarse approximation since some important parameters such as filling degree, particle size and material properties are not included. Comparison DEM simulation results of mechanical mixing by Kwapinska et al. (2006) with thermal mixing by Schlünder (1984) and Schlünder and Mollekopf (1984) demonstrated a large deviation, whereas the thermal mixing showed significantly higher values than mechanical mixing.

Shi et al. (2008) utilized couples of DEM-CFD and heat transfer calculation for simulation of bed heat transfer in a rotary drum for conduction-dominated and convection-dominated heat transfer. The authors concluded that the heat transfer is dominated by gas–solid conduction at low particle conductivities, while solid–solid conduction dominated at higher particle conductivities. This work only consisted of numerical simulation without validation from any experimental work. Figueroa et al. Figueroa et al. (2010) inspected the interaction between transient heat transfer and particle mixing in rotating cylinders by using TPD. The influence of heating rate on mixing rate also was investigated by varying the tumbler shapes, filling degrees and rotational speeds. This work is also numerical simulation without validation from experimental work.