EXPERIMENTAL INVESTIGATION OF THERMAL BED MIXING IN ROTARY DRUMS

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ABSTRACT

The transversal solid bed mixing was experimentally conducted 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. The mixing temperature in the solid bed was measured with thermocouples located at different bed height. The mixing behavior was investigated for various rotational speeds, filling degrees, materials and particle sizes.

INTRODUCTION

Rotary drums are widely employed in chemical and metallurgical industries for thermal treatment of powder and granular materials. The processes in rotary drums include mixing, drying, calcination of limestone, sintering of cement, reduction of iron ore, waste incineration, catalyst reactivation, etc. The mixing in rotary drums is one important aspect for quality and performance of the products. It depends on many parameters such as operational parameters (rotational speed, filling degree, material throughput, flow rate of gas), heating parameters (type of fuel, flame length and heat supply) and design parameters (diameter, length and inclination angle of the drum). The mixing occurs in two directions, axial and transverse direction whereas the transverse mixing is faster than axial mixing for few orders of magnitude [1]. Hence, the thermal efficiency of a rotary drum is predominantly defined by the amount of transverse mixing of the solid bed.

For a safe design and optimization of the process in a rotary drum, understanding the temperature difference within the solid bed is crucial. Particularly, when the material consists of different sizes, density or shape, segregation (de-mixing) will occur and generate temperature difference in the solid bed which will affect the product quality substantially. Therefore, temperature differences inside the bulk bed should be avoided to ensure a homogenous product quality.

The mechanical granular mixing was investigated previously by many researchers. Experimental works on transverse mixing in the rotary drum were done by using color tracer particles [2-5], image analysis [6,7] and radioactive particle tacking (RPT) method [8]. Several efforts have been done for modeling of transverse mixing [9,10] and simulation on mechanical mixing in rotary drum. The simulation was carried out with different approaches; mathematical simulation [11], discrete particle simulations (DPS) [12] and discrete

NOMENCLATURE

F	[%]	Filling degree
A_{drum}	[m^2]	Cross sectional area of rotary drum
$A_{solid\ bed}$	[m^2]	Cross sectional area of solid bed
$c_{p,S}$	[kJ/kg/K]	Heat capacity of solid bed
d_p	[mm]	Particle diameter
h	[mm]	Bed height
n	[rpm]	Rotational speed
R	[mm]	Drum radius
ε	[rad]	Filling angle
Θ	[deg]	Dynamic angle of repose
λ_S	[W/m/K]	Effective thermal conductivity of the solid bed
ρ_S	[g/cm³]	Bed density

element method (DEM) [13,14]. Furthermore, the thermal mixing in the rotary kiln was investigated using DEM approaches [15-17], coupled DEM with computational fluid dynamics (CFD) [18] and Thermal particle dynamics (TPD) [19].

Longitudinal and transverse mixing was investigated by Finnie et al. [13] using DEM approach for various rotational speeds and filling degrees. The transverse mixing were characterized by entropy-like mixing index. With the number of revolution, mixing speed was defined from the exponential function of mixing index. The influence of filling degree and rotational speed on mixing speed was determined. With same number of revolutions, the mixing speed is increased with lower rotational speed and filling degree. The transverse mixing of particles in rotating drum was investigated by Kwapinska et al. [14] using 2-D DEM. The simulations were done with various rotational speeds, drum diameter, filling degree and mean particle size. A comparison of simulated results using inter-particle interaction had a good agreement with the experimental data by Puyvelde et al. [7,10]. However, a comparison of thermal mixing by [20-21] and mechanical mixing demonstrated big deviation, where the thermal mixing showed significantly higher values than mechanical mixing. 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.

Shi et al. [18] utilized couples of DEM-CFD and heat transfer calculation for simulation of bed heat transfer in rotary kiln for conduction-dominated and convection-dominated heat transfer. The authors conclude that the heat transfer is dominated by gas–solid conduction at low particle

conductivities, while solid–solid conduction dominated at higher particle conductivities. The simulation was done for rotational speeds from 5 to 15 rpm, which is very high for industrial practice. In addition, this work was only numerical simulation without validation from any experimental work. Figueroa et al. [19] was inspected the interaction between transient heat transfer and particle mixing in rotating cylinders by using TPD. The influence of mixing rate on heating rate also was investigated by varying the tumbler shapes, filling degrees and rotational speeds. The authors introduced Péclet number and examined the impact of mixing on the relative importance of conduction and convection under vacuum conditions. The influence of effective thermal diffusivity on the mixing and heating was shown, where highly conductive material can effectively transmit heat with short period of time. This work is also numerical simulation without validation from experimental work.

Based on previous literature, a lot of works on mechanical mixing were done numerically and experimentally. However, few works have been done on thermal mixing in the solid bed. In the unavailability of experimental data, it is prudent to conduct experimental study on thermal mixing in rotating drum. Therefore, this work was conducted to study thermal mixing experimentally in a rotating drum. Two fractions of solid bed with different thermal conditions were mixed and the temperature was measured inside the solid bed during the mixing process. The influence of various rotational speeds, filling degrees, materials and particle sizes on mixing time and bed rotation was analyzed.

ROLLING MOTION AND TRANSVERSAL MIXING

During the transport along the axis of a rotary drum, the solid shows different forms of motion behavior. Experimental studies and modeling of transverse motion in rotary kiln motion were done by [22-24]. Mellmann [24] summarized the motion in transverse plane by using Froude number and filling degree as the mean of characterization. The motions divide to three main classes, namely slipping, cascading and cataracting. The transient behavior between the different motion types were researched by [25,26]. Slipping motion is happen as a result of slow rotational speeds and low friction between wall and solid bed. This motion type occurs without particle mixing in the solid bed, hence it is avoided in industrial application. Typical for cataracting motion are high rotational speeds and high centrifugal force. Therefore, the motion of the solid bed is discontinuous and partially particles flow into the free-board which results in an inhomogeneous mixing and, hence, avoidance in industries. The desired bed motion in rotary drums is the cascading, more precisely the rolling motion. Here the mixing of the particles in the solid bed is efficient because of the continuous circulation of the bed particles. Figure 1 illustrates qualitative mechanism of rolling motion in the cross-section area of a drum.

A rolling bed is characterized by the continuous flow of particles with a nearly constant slope of the bed surface, defined as the dynamic angle of repose, Θ. This slope is
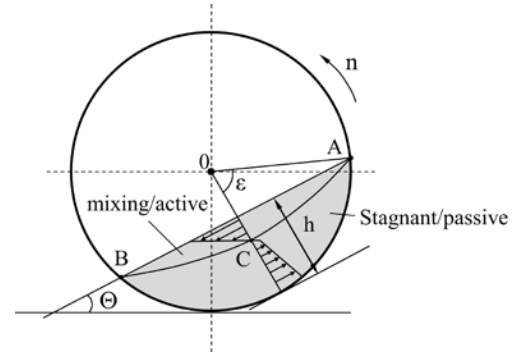

Figure 1 The mechanism of rolling motion in the cross-section area of a drum

dependent on the material properties of solid bed and wall friction. The rolling bed can be divided into two zones, namely a stagnant zone and the mixing zone. These zones are separated by a fictitious boundary layer ACB, where is approximately symmetric over the vortex point C. At first the passive or stagnant zone where the particles below the bed are transported in radial direction as a rigid body with the rotation speed of the wall from point B to A. No particle mixing occurs in this zone. After reaching the upper point A, the particles flow downwards on the free bed surface in a thin layer (active layer) with relatively higher velocities from point A to B. This is the particle mixing zone where the particles present radial and axial velocity components. Active layer is predominantly influence the mixing and temperature distribution inside the bed [27]. The mixing also dependent on filling degree of the solid bed, which is defined as volume of material occupied in the rotary drum. In geometric relation, it can be expressed as;

$$F = \frac{A_{\text{solid bed}}}{A_{\text{drum}}} = \frac{\varepsilon - \sin \varepsilon \cos \varepsilon}{\pi} \quad \text{with } \varepsilon = \arccos\left(1 - \frac{h}{R}\right) \quad (1)$$

with the filling angle ε and the solid bed height, h.

EXPERIMENTAL SETUP

A schematic diagram of the batch rotary drum used in the experiments for the investigation of thermal mixing in the solid bed is shown in Figure 2. It consists of a cylindrical drum made of steel with a wall thickness of 2 mm, an inner diameter of D = 600 mm and a length of L = 450 mm. The cylindrical drum is indirectly heated using three electric heaters with a total power of 4.5 kW, sufficient to reach a maximum solid temperature of 200°C. In order to record the temperature profile of the solid bed, 16 Type-K (NiCr-Ni) thermocouples were attached to a stationary measuring rod with specified distances from the inner drum wall as shown on the right hand side in Figure 2. The thickness of these thermocouples is 0.5 mm; hence the response time is quite fast because of their small diameter. The data from the thermocouples was transferred to a computer via cable for every millisecond interval. The collected data can be used directly for analysis.

At first, the material was divided into two fractions with ratio of 1:1. The first fraction was heated up in the drum to a

temperature of around 130°C. After temperature reach 130ºC, the heaters were turned off. Then, the drum rotation was stopped and the bulk bed was leave horizontally. Then, the second fraction with ambient temperature was filled on the hot layer, so at the beginning of the experiment the fractions were completely segregated. The drum rotation was started again and the temperature differences within the solid bed were measured.
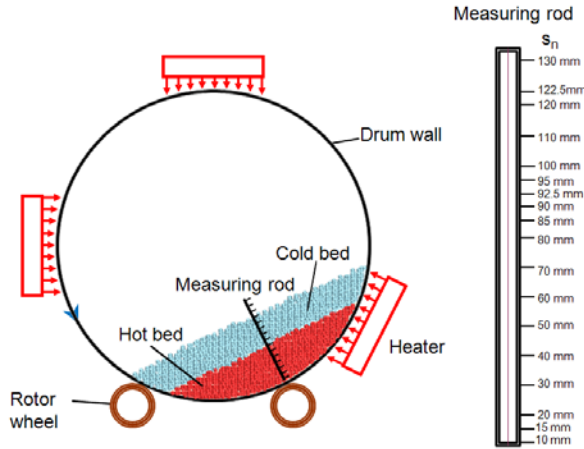

Figure 2 Cross section of a rotary drum and thermocouples arrangement

The experiments were performed with filling degree from 10 to 20% and rotational speeds from 1 to 6 rpm. Quartz sand and glass beads were used as test materials. The experimental parameters and test materials are shown in Table 1. The thermo-physical properties were given by the material producer while the bed densities and particle diameters were measured.

Table 1 Experimental parameters and test materials

Parameter	Parameter variation
Rotational speed	1 rpm, 3 rpm and 6 rpm
Filling degree	10%, 15% and 20%
Solid material	Quartz sand ;
	d_P = 0.2 mm:
	λ_S = 0.10 W/m/K, $c_{p,S}$ = 1.08 kJ/kg/K,
	ρ_S = 1.64 g/cm³
	Glass beads;
	d_p=see below:
	λ_S = 0.25 W/m/K, $c_{p,S}$ = 0.80 kJ/kg/K,
	ρ_S = 1.68 g/cm³
Particle diameter	d_P = 0.7; 1.3; 2.0; 3.0; 4.0 mm

RESULTS AND DISCUSSION

Figure 3 shows the temperature measurement with experimental time for glass beads with 20% filling degree and rotational speeds of 6 rpm. The upper part of the oscillating peaks represents the temperature values for the hot fraction while the lower part shows the temperature for the cold fraction. As mentioned before, the thermocouples were located

at different distance from the wall. Therefore, the temperatures were measured at different bed heights of the solid bed, from 10 mm from the wall till 130 mm from the wall. Before the mixing process starts, the highest temperature is measured by the thermocouple nearest to the wall (10 mm). The lowest temperature is indicated by the thermocouple with the farthest distance from the wall (130 mm).
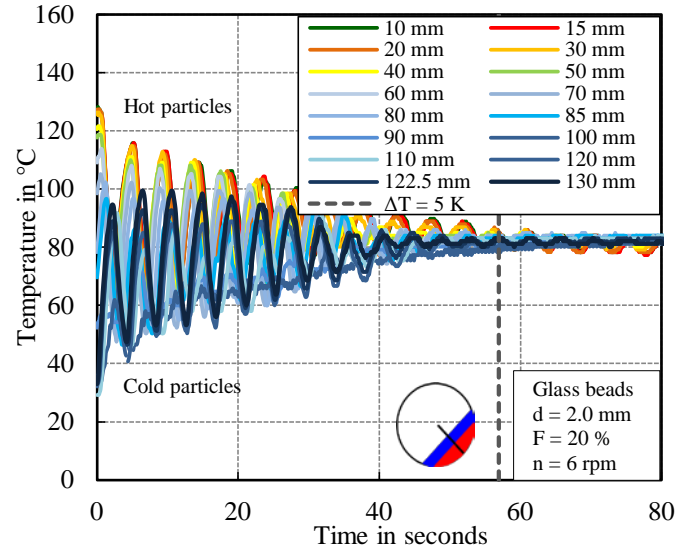

Figure 3 Temperature profiles of thermal mixing inside the bulk bed with experimental time

As the drum starts to rotate, the bed also rotates due to the rolling motion of the solid bed. During the rotation, cold particles move from the active to the passive layer whereas hot particles move from the passive to the active layer. Accordingly the temperature of 10 mm thermocouple decreases to a minimum and the temperature of 130 mm thermocouple increases to a maximum values. After reaching these extreme points, the particles rotate again from one layer to the other layer. Therefore, the temperature of 10 mm thermocouple increases to a new maximum while the temperature of 130 mm thermocouple decreases to new minimum values. The distance from one peak to another peak accounts for 1 bed rotation. The process is continuous until the solid bed reaches uniform temperature. With longer experimental time, the temperatures of the hot and cold particles become closer until they reach the mixing temperature. In the present work, temperature difference of 5 K inside the bed was set as a criterion for uniform mixing temperature. Hence, as shown by the dotted line in Figure 3, the mixing time for achieve uniform temperature is around 59 seconds for this example.

For a better understanding the mixing process, from the oscillating values in Figure 3, maximum peak and minimum peak were tabulated in Figure 4. These values were correlated with functions, which are needed to determine the mixing criterion. As shown before, the mixing time needed to obtain uniform temperature is 59 seconds (shown by dotted line).
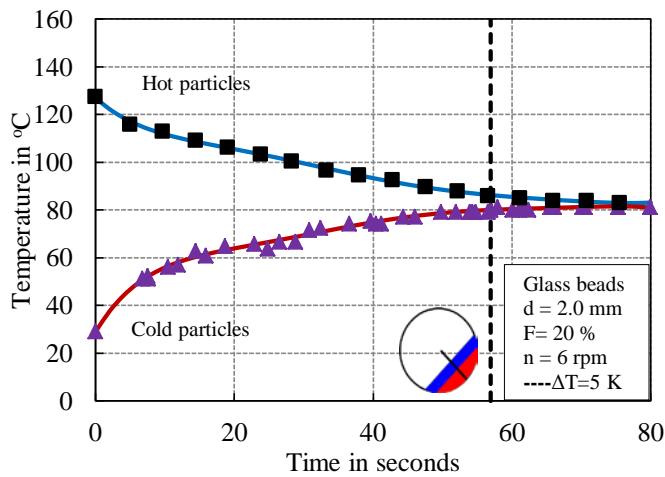
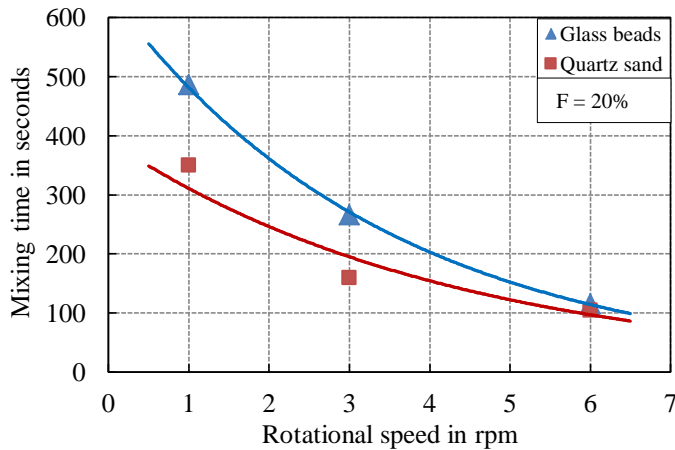**Figure 4** Determination of mixing time with defined criteria

Figure 5 Influence of rotational speed on mixing time

Figure 5 shows the influence of rotational speed on mixing time for glass beads and quartz sand at a constant filling degree of 20%. The mixing time for both materials decreases with higher rotational speeds. For high rotational speeds, e.g. 10 rpm, it is expected that the mixing time will close to minimum. The reduced mixing time with higher rotational speed concur with simulation and experimental results by [7,14]. With a higher rotational speed, the active layer thickness increases. Therefore, more particles located in the active layer and high particle velocity could be reached. This leads to more particle-particle interactions and enhance the mixing process. Furthermore, the number of bed rotation increases with the rotational speed which leads to a better thermal mixing of the solid bed.

Figure 6 shows the influence of filling degree on mixing time for glass beads and quartz sand at a constant rotational speed of 1 rpm. As depicted in Figure 6, the mixing time for both materials increases with higher filling degree. With higher filling degree, the number of particles in the drum increases; hence the relative size of active layer becomes smaller. Additionally, the solid mass fraction that has to be moved by

the drum is higher. Therefore, the rotations of the solid bed become slower and longer time needed to achieve uniform temperature. Slower mixing with higher filling degree agrees with previous works by [4,7,12-14].
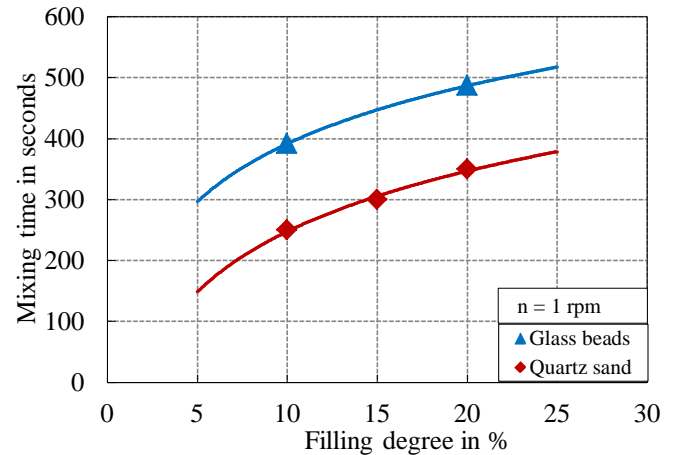

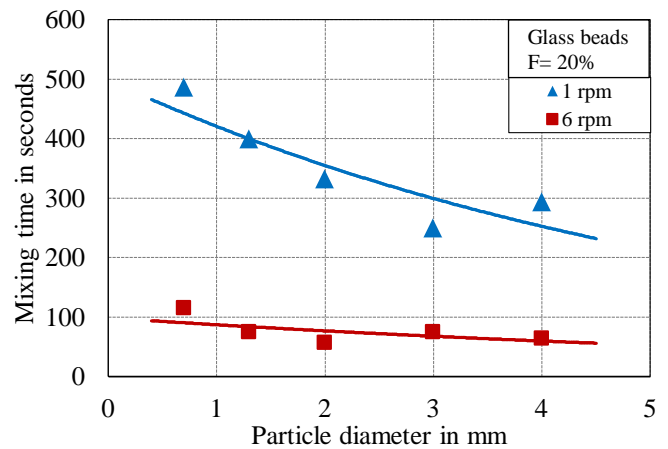**Figure 6** Influence of filling degree on mixing time

Figure 7 Influence of particle diameter on mixing time

The influence of particle diameter on mixing time for both 1 and 6 rpm is illustrated in Figure 7. The figure shows the solid bed of glass beads with constant filling degree of 20%. As shown, the mixing time decreases with bigger particle sizes. The influence of particle diameter on mixing time is more significant for 1 rpm than 6 rpm. With bigger particle sizes, the thickness of active layer increases and the number of particles in the active layer decreases. Therefore, more particle-particle interaction can occur in the active layer which enhances the thermal mixing inside the bed.

Figure 8 shows the influence of rotational speed on the number of drum rotation for glass beads and quartz sand at a constant filling degree of 20%. As an alternative of mixing time, the number of drum rotation also could be use as a criterion for mixing process. If the rotational speed is constant, then the trend for the number of drum rotation is equal to the mixing time. However, if the rotational speed is varied, the
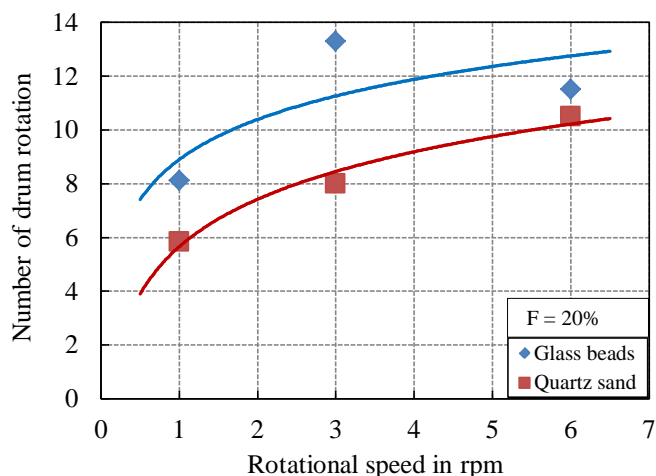
Figure 8 Influence of rotational speed on the number of drum rotation

mixing time differs from the number of drum rotation. As could be seen, the number of drum rotation increases with higher rotational speed.

CONCLUSION

Thermal mixing of bulk solid has been experimentally investigated in a batch rotary drum. The drum was filled with two fractions of granular material with different thermal conditions and the time needed for achieve uniform temperature, namely mixing time, was evaluated. The mixing time was investigated for various rotational speeds from 1 to 6 rpm, filling degree from 10 to 20%, particle sizes from 0.7 mm to 4 mm and two solid materials, glass beads and quartz sand. It was shown that the mixing time decreased with higher rotational speed, caused by more particle-particle interactions and increasing of number of bed rotation which enhances the mixing process. The mixing time also decreases with bigger particle size. As particle size increases, the active layer thickness also increased and the number of particle in the active layer decreased. Therefore, more particle-particle interaction can occur in the active layer and shorter time needed to obtain uniform temperature. In contrast, the mixing time increased with higher filling degree. With higher filling degree, the bed rotations become slower and longer time needed to achieve uniform temperature.

ACKNOWLEDGEMENT

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