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# ANALYSIS OF HEAT PENETRATION INTO THE SOLID BED OF ROTARY DRUMS

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## ABSTRACT

The heat penetration into the solid bed of rotary drums was experimentally investigated. An indirect heated rotary drum with a diameter of D=600 mm and a length L=450 mm has been used for this purpose. Temperature profiles of the gas, the drum wall and the solid bed were measured using 16 Type K thermocouples assembled on both a rotating and a fixed rod that attached inside the drum. Hence, the temperature distribution inside the solid bed was analyzed from these temperature profiles. Two different solid bed materials, steel spheres and glass beads, were used in the experiments. These materials differ in particle diameter and thermo physical properties (density, heat capacity and thermal conductivity). The rotational speed was varied from 1 to 6 rpm while the filling degree was varied from 10% to 20% to see their influence on the heat penetration in the moving solid bed.

## INTRODUCTION

Rotary kilns are processing apparatuses used for drying, calcining, or sintering in various industries such as mining, metallurgy, building materials and hazardous waste management. The temperature range of these processes extends from 100 to 2000°C. Rotary kilns are slightly inclined cylindrical drums, which rotate around its horizontal axis. The raw material is fed at the upper end and is gradually transported towards the lower end as the kiln rotates.

Rotary kilns can be heated directly or indirectly depending on the requirement of the processes. In an indirect heated rotary kiln, the contact heat transfer from the covered wall to the covered solid bed is dominant. Contact heat transfer also contributes up to 20% of the heat transfer to the solid bed in a directly heated rotary kiln. The contact heat transfer coefficient consists of a series of contact resistances between the wall and the particles and the penetration resistance inside the solid bed. The penetration resistance is influenced by the effective thermo physical properties of the solid bed.

The effective thermo physical properties, especially the effective thermal conductivity, are very important since they influence the temperature distribution inside the bed. Previous researchers have developed the mathematical model for the thermal conductivity of a packed bed [2, 7, 9, 13, 14, 15]. This distribution is significant since it leads to product quality issues. Furthermore, the bed segregation and process chemistry will influence the temperature differences inside the bed [1].

## NOMENCLATURE

| | | |
|---|---|---|
| $A_{drum}$ | [m²] | Total cross sectional area of the drum |
| $A_{solid\ bed}$ | [m²] | Cross sectional area of the solid bed |
| $c_{p,S}$ | [J/kg/K] | Solid specific heat capacity |
| $d_P$ | [m] | Particle diameter |
| $h$ | [m] | Bed height |
| $L$ | [m] | Length of the drum |
| $\dot{Q}_{total}$ | [W] | Total heat supplied |
| $\dot{Q}_W$ | [W] | Heat flow through the kiln wall |
| $\dot{Q}_{WS,\varepsilon}$ | [W] | Heat flow by radiation from the free wall surface to the free solid bed surface |
| $\dot{Q}_{WS,\lambda}$ | [W] | Heat flow by conduction from the covered wall surface to the solid bed |
| $\Delta T_{bed}$ | [-] | Temperature difference inside the bed |
| $R$ | [m] | Drum radius |
| T | [°C] | Temperature |
| $t_{contact}$ | [s] | Contact time |
| $\lambda_S$ | [W/m/K] | Solid bed conductivity |
| $\rho_S$ | [kg/m³] | Solid bed density |
| Special characters | | |
| F | [%] | Filling degree |
| $n$ | [rpm] | Rotational speed |
| $s_n$ | [mm] | Thermocouple distance |
| $\gamma$ | [rad] | Filling angle |
| Subscripts | | |
| min | | Minimum |
| max | | Maximum |
| W | | Wall |

For a safe design and optimization of a rotary kiln, the understanding of temperature distribution within the solid bed is rather important. Typically, for process simulation the temperature within the solid bed is taken as a mean temperature**.** This is not accurate since the temperature in the solid bed varies in the radial as well as the axial position as the kiln rotates.

The temperature distribution within the solid bed has not been studied thoroughly. It is not well understood since very high temperatures and the continuously rotating kiln make the temperature measurement inside the solid bed quite difficult. There are few experimental works on investigating the temperature distribution inside the solid bed [3, 4, 8, 10, 16]. However, the previous works were not addressed the influence of operational parameters on the temperature distribution within the solid bed.

Therefore, this experimental work is conducted for different operating conditions (filling degree and rotational speed) and different materials to study the influence of these parameters on the temperature distribution indide the solid bed. This work is an initial step in investigating the heat penetration and thermal conductivity of a moving solid bed.

## HEAT TRANSFER MECHANISM AND MOTION BEHAVIOUR

The heat transfer mechanism in rotary kilns is a complex phenomenon. It includes conduction, convection and radiation. Figure 1 illustrates the heat transfer mechanism in an indirect heated rotary kiln.

For indirect heated rotary drums, the drum wall, which is usually made of steel or graphite, is heated externally with $\dot{Q}_{\text{total}}$. The heat from the source is transported to the wall and then conducted through the wall $\dot{Q}_{\text{W}}$. A part of the heat radiates to the free solid bed surface $\dot{Q}_{\text{WS},\varepsilon}$ and the other part is conducted from the covered wall surface to the solid bed in the contact region, $\dot{Q}_{\text{WS},\lambda}$.

The covered and free surface area of the wall and solid bed depends on the filling degree of the solid bed. The filling degree can be defined as the ratio of the cross sectional area of the solid bed to the total cross sectional area of the drum as shown in Figure 1. In geometric relation, it can be expressed as

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

with the filling angle $\gamma$ and the solid bed height $h$. In a rotary drum, rolling motion is the desired motion behavior because it can realize perfect mixing of the solid bed. This motion is described by the subdivision of the solid bed into two regions, the passive layer in the lower region and the active layer. These layers are separated by a fictitious boundary layer (ACB). In the passive layer, the particles are lifted up to the upper region due to contact with the wall during the rotation of the drum. At the upper boundary line (CA), the particles are mixed up into the active layer and flow down due to gravity along the line (AB). At the boundary line (BC), particles are mixed out of the active layer and mixed into the passive layer. This process is continuously occurring, therefore the solid bed is well mixed.

Extensive experimental studies and modeling for the rolling motion were completed by Henein et al. [5, 6], Liu et al. [11] and Mellmann [12].

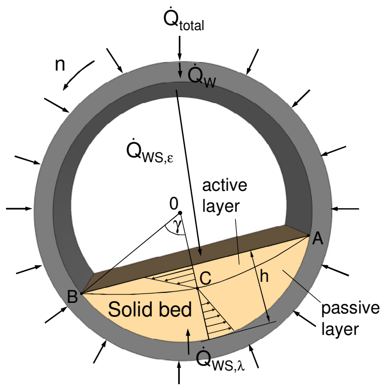

**Figure 1** Heat transfer mechanism in the cross section of indirect heated rotary kilns.

## EXPERIMENTS

### Experimental Setup and Test Materials

A schematic diagram of the batch rotary drum used in the experiments for the investigation of temperature distribution within 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 capacity of 4.5 kW, sufficient to reach a maximum temperature of 200$^{\text{o}}$C.

In order to record the temperature profile of the solid bed, 15 thermocouples were attached to a rotating rod with specified distances from the inner drum wall as shown in Figure 2. With this rotating rod, the radial temperature as well as the circumferential temperature profile of the solid bed could be measured simultaneously. In addition, a thermocouple was installed directly on the surface of the inner wall of the drum to simultaneously measure the wall temperature of the drum. Hence, overall 16 thermocouples were used to measure the temperature inside the drum. These thermocouples are Type K thermocouples, made of NiCr-Ni with a diameter of 0.5 mm. Another stationary measuring rod was installed and positioned in the solid bed at a defined circumferential position. This stationary measuring rod is used to assess delay of the thermocouples at the rotating rod. 16 thermocouples were attached at this stationary rod with similar radial spacing to that of the rotating rod. The temperature differences between the two measuring rods are considered to be negligible as discussed by Sonavane and Specht [17]. The response time of the thermocouples is fast because of the small diameter of the thermocouples. Therefore, the temperature measured by rotating thermo elements was considered to have good accuracy for the investigation of temperature distribution.

In the experiments, steel spheres and glass beads were used as test materials. The effective thermo physical properties and the particle diameter of these materials are shown in Table 1.

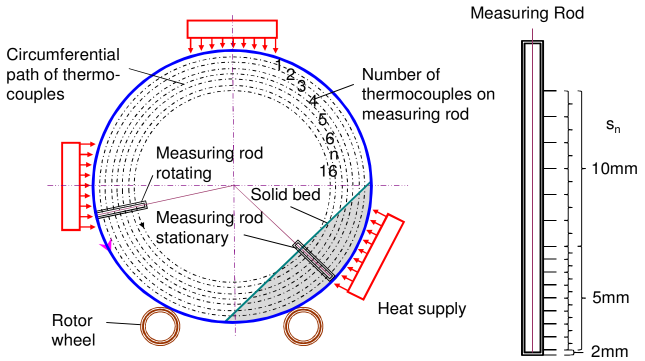

**Figure 2** Schematic cross section of the batch rotary drum and the thermocouples arrangement.

**Table 1** Test materials and their properties.

| Testing material | Glass beads | Steel spheres |
|---|---|---|
| Particle diameter $d_p$ (mm) | 0.7 / 2.0 | 0.8 / 2.0 |
| Bed density, $\rho_S$ (kg/m$^3$) | 1680 | 4827 |
| Specific heat capacity, $c_{p,S}$ (J/kg/K) | 800 | 465 |
| Thermal conductivity, $\lambda_S$ (W/m/K) | 0.25 | 1.37 |

### Experimental Analysis

The measured circumferential temperature profiles for steel spheres with a filling degree of F=10% and a rotational speed of n=1rpm after 30 minutes experimental time are shown in Figure 3. The thermocouples distanced from the wall measured the air temperature inside the rotary drum initially from $0^o$ to $78^o$ (not shown in the figure). After $78^o$, the thermocouples located nearer to the wall immersed earlier in the solid bed than farther thermocouples. The rise in temperature was initially recorded by the thermocouple with 2 mm distance from the wall at about $79^o$ while the thermocouple with 62 mm distance from the wall recorded a temperature increase lastly at about $90^o$. The farthest thermocouple (62 mm) emerged out initially at about $147^o$ while the nearest thermocouple (2 mm) emerged out from the bed lastly at about $170^o$. As seen in Figure 3, a uniform temperature of the solid bed is obtained from $115^o$ to $140^o$, but the temperature within the solid bed decreases with radial distance from the wall.

Figure 4 shows the temperature within the solid bed from $120^o$ to $140^o$ with respect to circumferential position. It can be seen that the temperature difference within the solid bed in the radial direction is about 17K. In this experiment, the solid bed temperature is only around $160^o$C after two hours experimental time. For a real process, high temperatures up to $2000^o$C could be achieved. To interpret the temperature difference for a certain process temperature, it is therefore important to define it dimensionless.

The relative temperature difference in the solid bed, $\Delta T_{bed}$ was calculated with

$$\Delta T_{bed}=\frac{T_{max}-T_{min}}{T_{max}} \qquad (2)$$

which is related to the maximum temperature of the bed.

Here $T_{max}$ and $T_{min}$ are the maximum and minimum temperature within the solid bed respectively in degree Celsius ($^o$C).

The temperature distribution inside the moving solid bed was investigated with different operating conditions. The rotational speed was varied from n=1 to 6 rpm while the filling degree was varied from F=10% to 20% to see their influence on the temperature distribution in the moving solid bed.

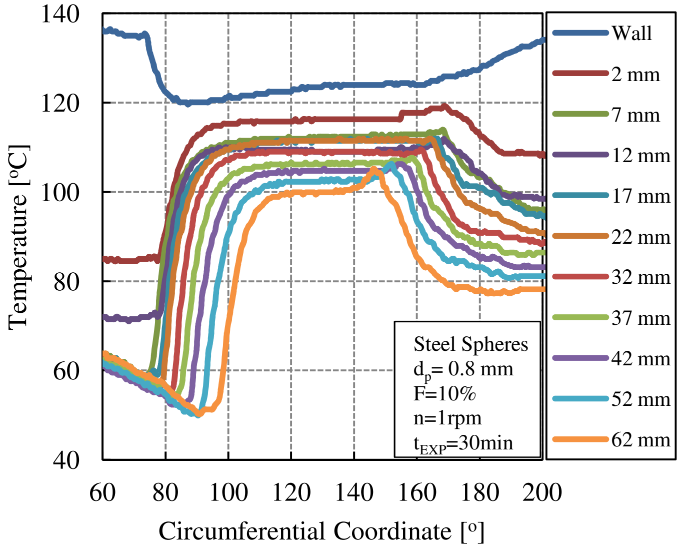

**Figure 3** Circumferential temperature profiles of the wall and the solid bed.

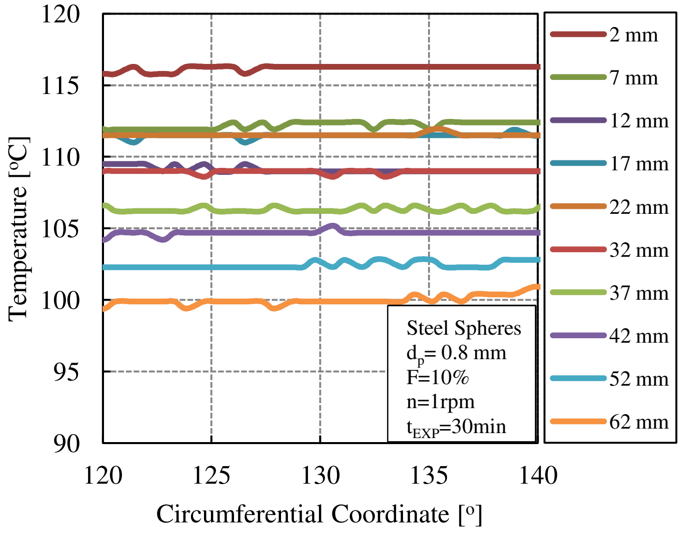

**Figure 4** Circumferential temperature profile of the wall and the solid bed (close up of Figure 3).

## RESULTS AND DISCUSSIONS

Figure 5 shows the temperature difference inside the solid bed during the measurement. It can be seen that the temperature difference inside the solid bed is increases at the beginning. This is because initially the material is heating up from the ambient temperature. After about 10 minutes, the temperature difference begins to decrease and reach steady state as a result of uniform heat distribution during the experimental time.

This figure also shows the influence of the effective thermo physical properties on the temperature difference inside the solid bed during the measurement. It can be seen that the temperature difference for steel spheres is lower than that for glass beads. Good heat penetration is shown by the low temperature difference inside the solid bed. Steel spheres have approximately 3.9 times higher bulk density, about 5.5 times higher thermal conductivity and about half of the specific heat capacity than that of the glass beads. Heat penetration resistance inside the solid bed reduces with higher effective thermo physical properties. A higher effective thermal conductivity promotes better heat penetration within the solid bed thus reducing the temperature difference.

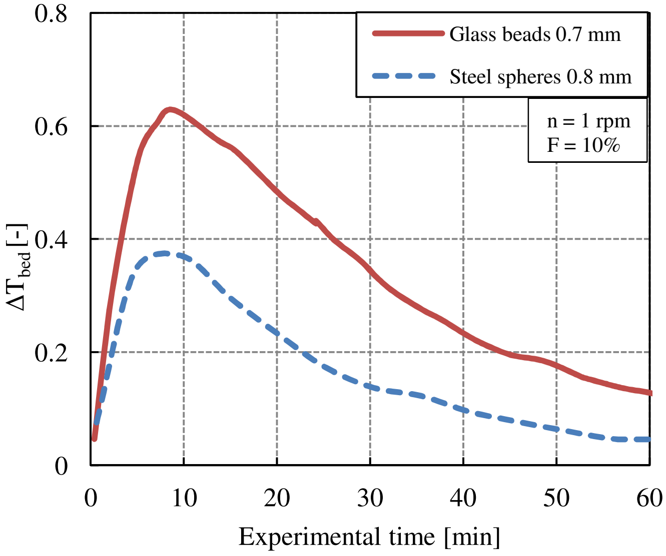

**Figure 5** Temperature difference inside the solid bed during experimental time.

The influence of rotational speed for 10% filling degree on the maximum temperature difference inside the solid bed is shown in Figure 6. The maximum temperature difference inside the solid bed decreases with higher rotational speeds. As the rotational speed increases, the number of bed circulations increases thus promoting better mixing within the solid bed. Hence, the temperature difference inside the solid bed decreases. As discussed before, the temperature difference inside the solid bed for steel spheres is lower than for glass beads.

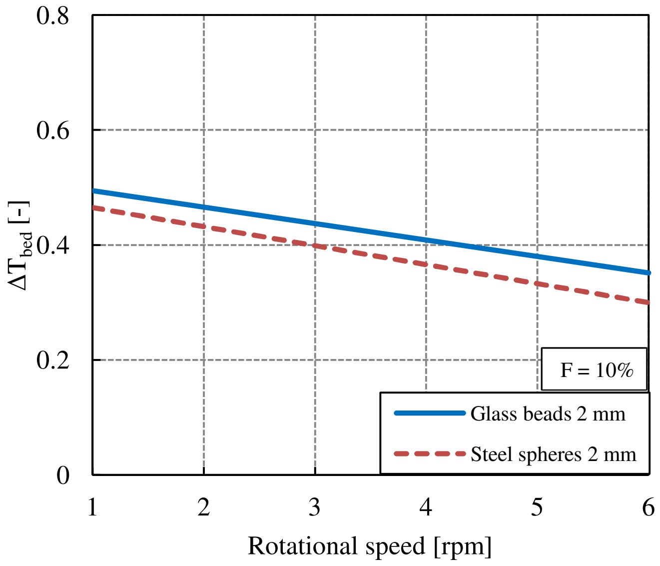

**Figure 6** The maximum temperature difference inside the solid bed in dependence on rotational speed for different materials.

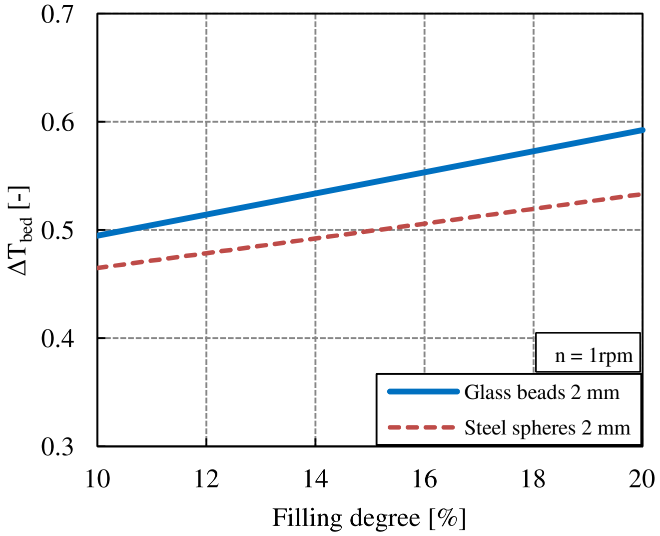

**Figure 7** The maximum temperature difference inside the solid bed in dependence on filling degree for different materials.

For a constant rotational speed of n=1 rpm, the influence of the filling degree on the temperature distribution inside the bed is illustrated in Figure 7. It can be seen that the maximum temperature difference increases with higher filling degrees. As the filling degree increases, the numbers of bed circulations during one drum rotation decreases. Hence, the material mixing in the transverse plane decreases thus reduces the heat penetration inside the solid bed.

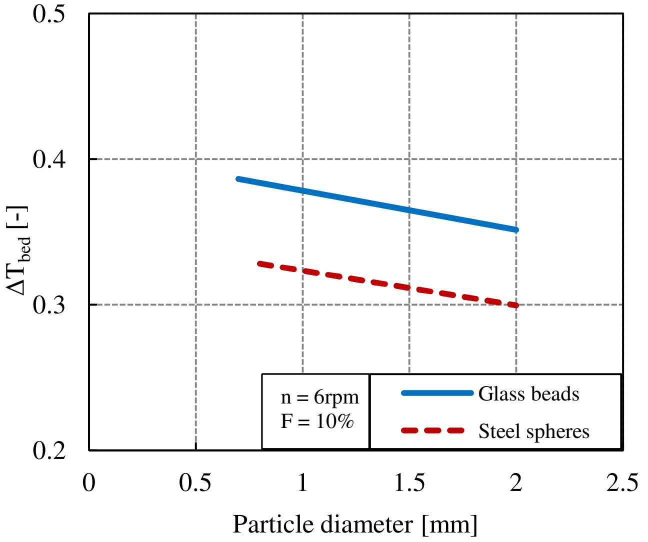

**Figure 8** The maximum temperature difference inside the solid bed in dependence on diameter of particles.

Figure 8 shows the influence of particle diameter on the maximum temperature difference inside the solid bed. The maximum temperature difference decreases with higher particle diameters.

## CONCLUSION

The temperature distribution within the solid bed has been investigated. Steel spheres and glass beads were used as test materials with variation in rotational speed (1 and 6 rpm) and filling degree (10 and 20%) of the drum. It is shown that the maximum temperature difference inside the solid bed decreases with higher rotational speeds, lower filling degrees and bigger particle sizes. In addition, the effective thermo physical properties have a significant influence on the temperature distribution and heat penetration within the solid bed. As the effective thermo physical properties become higher, the temperature difference within the solid bed reduces. This is due to the lower heat penetration resistance inside the solid bed. In further steps, a mathematical model for the heat penetration and effective thermal conductivity for moving solid beds in rotating drums will be developed.

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