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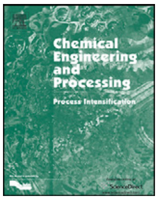

Temperature distribution within the moving bed of rotary kilns: Measurement and analysis

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ABSTRACT

Inadequacies in the temperature measurement within the moving bed have hindered a thorough understanding of the processes occurring within rotary kilns. A new measuring system, consisting of thermocouple arrays, a radio-transmitter, a radio-receiver and a computer monitor is introduced in this paper. With it, the 3D temperatures within the moving bed, as well as the temperatures of the freeboard gas and the kiln wall, can be measured and saved automatically. Experiments with sand on a co-current pilot kiln demonstrated that, in the passive layer of the moving bed, the temperatures were approximately constant in the circumferential direction. In the radial direction, however, large temperature difference was observed within the bed near the feed end of the kiln, and the difference became smaller as the bed went progressed through the kiln. This temperature measuring system can be used to obtain data over a wide range of operating conditions for use in engineering design. The obtained results may give new thoughts in theoretical modeling of heat transfer within the moving bed of rotary kilns.

1. Introduction

Rotary kilns are chemical reactors widely used in the metallurgical and chemical industries to handle bulk materials. The material to be treated is fed into a cylindrical pipe and transported forwards due to the rotation and inclination of the pipe. During the transport process, the material exchanges heat with the energy carrier (combustion gas for example), being dried or calcinated. Despite research efforts, the heat transfer process within the material bed has not been well understood [1]. One of the reasons is the lack of experimental data needed to test the heat transfer models. Many factors, for example, the continuously rotating parts of the kiln and the moving bed, make the temperature measurement within the material bed rather difficult. There are a few experimental studies reported in the literature [2–4]. However, only the temperatures at the bed surface or the temperatures near the kiln wall were measured due to technical limitations. The temperatures at different depths of the bed were not investigated. In this paper, a new temperature measuring system using radio transmission technology is described that enables continuous temperature measurement within the moving bed in three dimensions, and the experimental results are discussed.

2. Experimental

2.1. Experimental apparatus and measuring technique

The pilot kiln has a length of 6.7 m and an outer diameter of 400 mm. The wall thickness is 75 mm, consisting of a 70 mm refractory and a 5 mm steel shell (Fig. 1). The inclination of the kiln can be varied from −1° to +2° and the rotation speed of the kiln is adjustable in the range of 0–3.25 rpm. The kiln is fired on natural gas using a programmable burner with a maximal capacity of 70 kW. The materials are fed into the kiln from a storage hopper, co-currently to the gas flow. In order to prevent overflow, a dam was installed at the feed end of the kiln.

Along the kiln length, four holes (‘measuring socket’) are drilled through the kiln shell (Fig. 1) to install thermocouples. In each socket, thermocouples are inserted into the kiln with different radial distances to the center point of the kiln cross-section (Fig. 2), so that temperatures of the gas, the material bed and the kiln wall can be measured. Since the thermocouples rotate continuously together with the kiln, the thermocouples may stay in the material bed and in the gas phase in one rotation. In order to determine the circumferential position of the measuring point, a pendulum is mounted on the kiln wall to measure the rotation angle ϕ ($\phi = 0$–360°). In this way, temperature profiles can be obtained as a function of the rotation angle at each axial position of the kiln, leading to a three-dimensional temperature measurement. Signals from the thermocouples and the pendulum are routed to a sender

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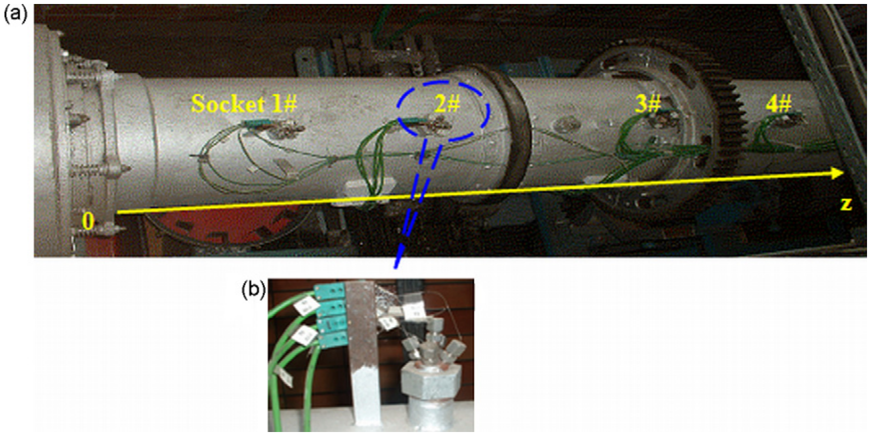

Fig. 1. (a) The pilot rotary kiln with measuring sockets and (b) measuring socket 2# with thermocouples inside.

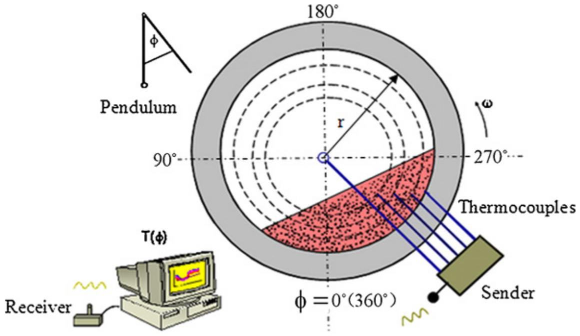

Fig. 2. The temperature measuring system.

and then transmitted to a receiver via radio. The measured values are saved automatically in a computer and displayed on the screen in real time.

2.2. Experimental details

In order to monitor the transient change of the temperature, quick response thermocouples (NiCr–Ni, type K; diameter 0.3 mm) were selected. Tests with a sudden change of temperature to the thermocouples showed a response time of about 2 s to reach 90% of the temperature change. In this experiment, twenty thermocouples are used. Detailed locations of the thermocouples are summarized in Table 1. Thermocouples with the radial distance of $r = 120\,\text{mm}/105\,\text{mm}/85\,\text{mm}/65\,\text{mm}$ serve to measure the temperatures within the material bed (the distance between the bed surface and the kiln axis is 45 mm), while thermocouples with $r = 125\,\text{mm}$ are buried in the inner wall to measure the temperatures of the inner wall. The freeboard gas temperatures are obtained using shielded thermocouples inserted into the middle of the cross-section of the kiln ($r = 0\,\text{mm}$). In order to obtain more information about the temperature distributions within the material bed, thermocouples with $r = 0\,\text{mm}$ had to be abandoned at sockets 2# and 3#. Nevertheless, the gas temperature can be approximated based on measurements from other thermocouples ($r = 120\,\text{mm}/105\,\text{mm}/85\,\text{mm}/65\,\text{mm}$) that pass through the material bed and the gas phase alternately.

Table 2
Running conditions of the kiln and the burner.

Rotation speed of the kiln	3.25 revolutions/min
Inclination of the kiln	1.9°
Feed rate of the sand	85 kg/h
Flow rate of the air	27.68 m^3/h
Flow rate of the natural gas	2.91 m^3/h

Dry and inert sand was used as testing material (bulk density = 1370 kg/m^3, mean particle diameter = 0.35 mm, dynamic angle of repose = 33°, heat capacity at 20 °C = 0.759 kJ/kg/K, effective thermal conductivity = 0.2 W/m/K). The operating conditions of the kiln and the burner are summarized in Table 2. Under such conditions, the bed moves under the rolling mode with a bed depth of approximately 80 mm at the four axial positions. The temperature of the combustion gas shows a maximum of about 1000 °C. The kiln was heated for about 3 h until a steady state (the wall temperatures at each measuring position did not change with time any longer) was reached. After that the burner and the kiln were stopped.

3. Results and discussion

3.1. Temperature profiles of the material, the gas and the kiln wall

For data analysis, it is convenient to use an auxiliary rotation angle defined as

$$\phi' = \begin{cases} \phi & 0^\circ \le \phi < 180^\circ \\ \phi - 360^\circ & 180^\circ \le \phi \le 360^\circ \end{cases} \qquad \phi' \in [-180^\circ, 180^\circ]. \tag{1}$$

With it, the region of the material bed can be described by one range ($-90^\circ \le \phi' \le 90^\circ$) instead of two separated ranges ($\phi = 0$–90°

Table 1
The locations of the thermocouples in the pilot kiln.

Socket no.	Axial distance (z) from the feed end of the kiln	Radial distance (r) from the axis of the kiln					
		125 mm (in the wall)	120 mm	105 mm	85 mm	65 mm	0 mm
1#	0.5 m	Y[a]	Y	Y	Y	N	Y
2#	0.8 m	Y	Y	Y	Y	Y	N
3#	1.39 m	Y	Y	Y	Y	Y	N
4#	1.795 m	Y	Y	Y	Y	N	Y

[a] The letter Y means that a thermocouple is available at that position; the letter N means that no thermocouple is installed at that position.