Chemical Engineering Science 65 (2010) 3059–3063

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Predicting the fraction of the mixing zone of a rolling bed in rotary kilns

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ARTICLE INFO

Article history:
Received 14 May 2009
Received in revised form
23 January 2010
Accepted 27 January 2010
Available online 1 February 2010

Keywords:
Chemical reactors
Particle Technology
Granular materials
Rotary kiln
Rolling motion
Mathematical modeling

ABSTRACT

The thermal efficiency of a rotary kiln is predominantly influenced by the amount of lateral mixing of the material bed. In this paper, the fraction of the mixing zone in the material bed is predicted for the rolling motion. For a given material, the fraction is found to depend only on three dimensionless variables—the ratio of the particle diameter to the kiln diameter, the Froude number and the filling degree. Experiments were carried out on a rotating cylinder with beans as testing material. The predicted results are in good agreement with the measurements with a maximal error of 12%. The fraction of the mixing zone is then analyzed for industrial rotary kilns. Its value is found to increase approximately linearly with increasing Froude number and the dynamic angle of repose of the material. For all investigated cases, the fraction of the mixing zone lies in the range of 20–45%. Results of this study can provide orientating values of the mixing zone fraction, which are needed to calculate the thermal efficiency of the rotary kiln.

1. Introduction

Rotary kilns are widely used in the chemical and metallurgical processes. The material to be treated is fed into a cylindrical pipe and transported forward 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. The heat transfer mechanism is strongly coupled with the motion behavior of the material (Kwapinska et al., 2008; Chaudhuri et al., 2006; Queck, 2002; Kelbert and Royere, 1991). For a material bed under the rolling motion, it has been demonstrated that the thermal efficiency of the kiln increases gradually as the fraction of the mixing zone in the material bed increases (Kelbert and Royere, 1991). Furthermore, the fraction of the mixing zone is also an important parameter in theoretical modeling for solid mixing and material transport in rotary kilns (Mu and Perlmutter, 1980).

Many studies have been carried out to investigate the thickness of the mixing zone (Sanfratello et al., 2007; Jain et al., 2002; Bonamy et al., 2002; Orpe and Khakhar, 2001, etc.). In most cases, however, only the maximal thickness was measured, or the material bed is not confined to the rolling motion occurring at low to medium rotating speeds. Significant studies on the fraction of the mixing zone are relatively rare. Attention is given herein to predict the fraction of the mixing zone of a rolling bed based on a previously developed analytical model. The results are compared with measurements carried out on a rotating cylinder with beans as testing material. Factors influencing the fraction of the mixing zone are then analyzed for large industrial rotary kilns.

2. Fraction of the mixing zone

A rolling bed is characterized by the continuous flow of particles (Fig. 1) with a nearly constant slope of the bed surface Θ (defined as dynamic angle of repose). The bed can be divided into two zones: (i) the stagnant zone (ADBCA), where the particles are transported as rigid body with the rotation speed n of the wall. No particle mixing occurs in this zone; (ii) the mixing zone (ABDA) where the particles flow downwards with relatively higher velocities. The boundary line between the mixing zone and the stagnant zone is approximately symmetric over the vortex point D.

For direct-fired rotary kilns, the heat is mainly transported through the mixing zone into the interior of the material bed (see Ref. Queck, 2002). The fraction of the mixing zone (shortened as *FMZ*), defined as the ratio of the mixing zone area A_m to the whole bed area A_{bed}

$$FMZ = \frac{A_m}{A_{\text{bed}}} 100\% \qquad (1)$$

is an important parameter to calculate the heat transfer. Several theoretical models are available to calculate the local thickness $s(x)$ of the mixing zone (Mellmann et al., 2004; Gray, 2001; Ding

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0009-2509/$ - see front matter
doi:10.1016/j.ces.2010.01.031

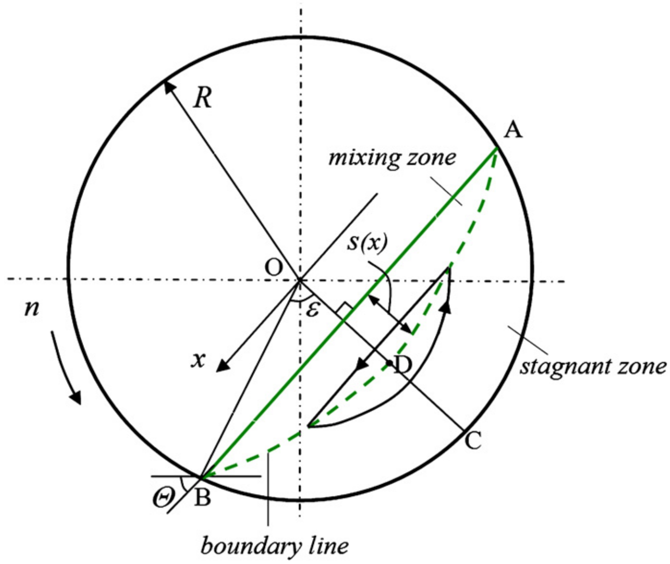

Fig. 1. The rolling motion.

et al., 2001; Elperin and Vikhansky, 1998; Boateng 1998; Khakhar et al., 1997, etc.), with which A_m can be calculated. Most of these models, however, contain a fitting parameter, which has to be adjusted in such a manner so that the calculated results should be in good agreement with the experimental data. Some of these models are too extensive and complicated for practical purposes. In the following section, the relatively simple analytical model developed by the authors in the previous work (Liu et al., 2006) will be used to calculate the thickness of mixing zone without introducing any fitting parameter. The introduced symbols are defined either in Fig. 1 or in the Notation.

According to Liu et al. (2006), the local thickness of the mixing zone can be described in dimensionless form as

$$\delta(\xi)=\frac{\xi-\xi_0}{\tan\Theta}+\frac{1}{k\sin^2\Theta}\ln\frac{2+\sin(2\Theta)k\xi_0}{2+\sin(2\Theta)k\xi}+\frac{d}{D} \quad (2)$$

where δ is the dimensionless thickness and ξ the dimensionless x-coordinate with respect to the cylinder radius R

$$\delta=\frac{s}{R},\quad \xi=\frac{x}{R}. \quad (3)$$

The constants k and ξ_0 are functions of the repose angle Θ and operating parameters (particle to cylinder diameter (d/D)), Froude number Fr, fill angle ε (related to filling degree f)

$$k=\frac{\tan\Theta-\tan(1.32\Theta+0.32\Theta f+10\pi\sqrt{(d/D)Fr})}{\sin\varepsilon} \quad (4)$$

$$\xi_0=-\sqrt{(\sin^2\varepsilon)-2(d/D)(1+\cos\varepsilon)}. \quad (5)$$

With known thickness $\delta(\xi)$ [Eq. (2)], the area of the mixing zone can be calculated through integration as

$$A_m=(D^2/2)\int_{-\sin\varepsilon}^{0}\delta(\xi)\,d\xi. \quad (6)$$

Substituting Eq. (6) and the equation for the bed area

$$A_{\mathrm{bed}}=\frac{\pi D^2}{4}f \quad (7)$$

into Eq. (1), the fraction of the mixing zone can be calculated as

$$FMZ=\frac{2}{\pi f}\int_{-\sin\varepsilon}^{0}\delta(\xi)\,d\xi\times 100\%. \quad (8)$$

It can be seen that *FMZ* depends only on the material property (Θ) and the three dimensionless parameters (f, Fr, d/D).

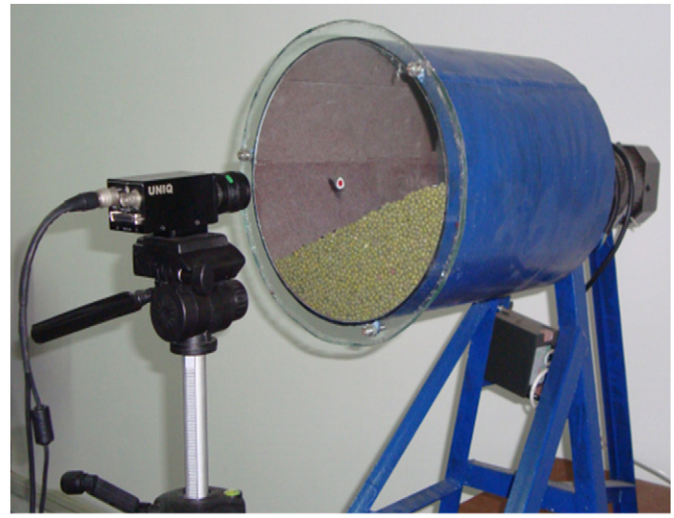

Fig. 2. Experimental set-up.

3. Experiments on a rotating cylinder

Experiments were carried out on a rotating cylinder to measure the fraction of the mixing zone of a rolling bed. The experimental set-up (Fig. 2) consists of a horizontal steel cylinder ($D\times L$=250 mm×310 mm) with a transparent glass plate at the front. To avoid unwanted sliding motion, the inner wall of the cylinder is glued with sandpaper (Type180). In the experiments, dry beans are used as testing material (d=3.50 mm, Θ=34°). The cylinder is partially filled with beans (f=0.248, 0.39) and rotated by a geared motor with rotation speeds n ranging from 4.86 to 13.3 rpm, resulting in the rolling motion of the material bed.

A digital camera (resolution=3648 × 2736 pixels) is installed perpendicularly to the plane of the glass plate to take the images of the rolling bed, using low shutter speeds so as to obtain particle streamlines. With the images and the software MariSoft Digitizer®, the geometrical position of the free bed surface and that of the boundary line between the static zone and the mixing zone can be obtained by joining the corners of the streamlines in the image (Fig. 3), with the origin of the coordinate system at the axis of the rotating cylinder. A typical measured profile of the mixing zone is also shown in Fig. 3. A polynomial of degree 5 is fitted to the boundary line curve. With such figures, the area of the mixing zone can be measured by MariSoft Digitizer and the value of *FMZ* can be determined based on Eqs. (1) and (7). This process is repeated for three images and the average value of *FMZ* is used. The resulting measuring error of *FMZ* is ±1%.

Measured values from seven experiments are listed in Table 1. For comparison, predicted values based on Eq. (8) are also included. It is apparent that *FMZ* increases with increasing rotation speed and decreases as the filling degree increases. For all experiments, the values of *FMZ* vary in the range of 16–28%. The predicted results agree well with the measurements, with a maximal relative error of −12% at the high filling degree f=0.39.

4. Predicting the fraction of the mixing zone for industrial rotary kilns

In practice, it is nearly impossible to measure the fraction of the mixing zone on an industrial rotary kiln due to its large dimension and the dust and smoke inside the kiln. Therefore, theoretical models have to be used to predict the value of *FMZ*. As discussed in Section 2, *FMZ* depends only on the material property