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Numerical simulation of three-dimensional unsteady granular flows in rotary kiln

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ABSTRACT

The granular particle motion with rolling mode in rotary kiln is investigated using a three-dimensional mathematical model based on the Euler–Euler two-phase flow and the kinetic theory of granular flow. The mathematical model verified by comparing with the published experimental data is used to simulate performance of an inclined rotary kiln. The angle of inclination and the residence time of particles in rotary kiln are taken into account. The active layer thickness can be calculated by observing the particle velocity change from positive to negative values. The stagnation point at the bottom of the free flowing zone is the interface between the active layer and the passive layer. Simulations show that the active layer of the charge end of the rotary kiln is thin and particle velocity is low. With the increase of axial distance, the active layer thickness and velocities of granular particles increase respectively, the thickness of the active layer and velocities of particles close to the discharge end of the rotary kiln decrease. A fourth-order polynomial velocity profile can be obtained from the numerical simulation results. Apart from providing a computationally efficient tool to simulate kiln performance, the results discussed here will provide a useful basis for the development of comprehensive three-dimensional models of rotary kilns.

1. Introduction

Rotary kilns are used by industry to carry out a wide variety of material processing including calcinations of limestone, reduction of oxide ore, reclamation of hydrated lime, calcination of petroleum coke and waste incineration. Material processing within the rotary kiln is studied aiming at gaining detailed knowledge of particle movements and heat transfer through granular media, which provides information on how to improve the mixture of granular particles and the quality of products.

Six flow regimes have been identified to describe the particle motion in a rotary kiln. They are slipping, slumping, rolling, cascading, cataracting and centrifuging mode respectively [1]. According to J. Mellmann [2], scaling criteria for the bed behavior are found to be the Froude number, filling degree, wall friction coefficient, ratio of particle to cylinder diameter, angle of internal friction, and dynamic angles of repose.

Among the various modes of the granular motion in rotary kilns, the slumping mode and the rolling mode is frequently investigated since it is often preferred in industrial operations. The percent fill of the industrial kilns is often between 8% and 15%, while rotation speed lies in the range of 1 to 5 rpm. According to Boateng et al. [3], for the rolling mode, the bed material can be divided into two distinct regions in the transverse plane [4]. They are, namely, a relatively thin 'active' region in the upper part of the bed and a thick 'passive' region near the rotary kiln wall. Boateng et al. [3] assumes that velocity vectors within the active layer are all parallel to the bed surface and vary in a parabolic way, while in the passive layer they vary linearly. In the passive region, particles move as a rigid body, and mixing are virtually negligible. The results derived from the experiment are useful in practice and in the mathematical modeling of the slumping–rolling transition.

Experiments on the continuous flow of granular material in the transverse plane of a rotating drum have been carried out with the aim of understanding the rheological behavior of materials in rotary kilns. In the experiment, measurement techniques are employed to measure flow characteristics such as particle velocities, granular temperature, and solid volume fraction. An analytical expression based on the previous numerical model [5] for calculating the profile of the active layer thickness in a rolling mode of the rotary kilns is proposed by Liu et al. [6]. The experimental results could provide guidance in the selection of constitutive relations which might enable granular flow modeling for rotary kilns.

Orpe et al. [7] experimentally investigates the flow of different materials in rotating cylinders. Experimental measurements obtained by flow visualization show that the flow in the active layer depends primarily on the Froude number ($Fr = \omega^2 R/g$, where ω is the rotation angular speed and g the acceleration due to the gravity) and size ratio ($s = d_p/R$, particle diameter to cylinder radius). It is clearly seen, in the experiment, that the surface flowing layer becomes thicker and more *S* shaped at high values of *Fr* and the layer thickness profiles become increasingly skewed with increasing *Fr* and decreasing *s*. Also, J M. et al. [8] proposes that for large particles, active layer thickness and the shear rate are controlled primarily by the *Fr* and *s*, whereas material properties have a secondary effect. A scaling relation [9] is first derived with the consideration of incomplete similarity associated

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with respect to *Fr* and *s*. Amarathe et al. [10] investigates the effect of density, friction coefficient, surface quality and particle geometry on the mixing particles. The results show that the *Fr* alone is not enough to completely characterize the rolling regime. The rotating cylinders are placed horizontally for easy measurement in the above experiments.

In parallel with the experimental work, several mathematical models have also been proposed aiming at understanding the kinetics and mechanisms of gas-solid systems. There are generally two kinds of models in two-phase flow simulations: Euler–Lagrange model and Euler–Euler model. The difference between the two models lies in the different treatments of the movement of the particles. In the first model, gas phase is regarded as continuum phase while particles are seen as dispersed phase. It is mainly tracked the trajectories of individual solid particles. Yang et al. [11] investigates the granular flow dynamics in different regimes using the discrete element method. The relationship between the angle of repose of the moving particle bed and the rotation speed is analyzed systematically in different regimes. Discrete Element Modeling (DEM) study is conducted to help understand flow processes and explain mixing mechanisms in mixing equipment based on the rotating drum. That the axial mixing is purely a dispersive mechanism and the radial mixing is dominant in rolling region is observed in that work [12]. 2D DEM is applied for simulating particle mixing in rotating drum by Xu et al. [13]. The simulations reveal that mixing behaviors are mainly affected by particle density and size, while the effect of frictional coefficient is less significant. In the latter model continuous medium model is used, which has a long history going through different stages including non-slip model, little-slip two-fluid model, slip-diffusion two-fluid model [14]. Depending on Euler model, Yassine et al. [15] uses fluent software to investigate the dynamic characteristics of granular flow in the transverse plane. The effects of angle of inclination and charge end and discharge end of the granular particle of the kiln on flow characteristics of granular particle are not considered in the above numerical studies.

A fundamental characteristic of granular flows in the rotary kiln is that they are typically restricted to thin layers of rapid surface flow. Thus, a complete understanding of surface flows is a key for an accurate representation of the dynamics of the entire flow. Several two-dimensional models have been proposed to describe the granular flow in the rotary kiln. However, attempts to predict conditions within the bed in 3D have been rare. The objective of this paper is to develop a three-dimensional mathematical model based on the kinetic theory of granular flow and the Eulerian method to explore the particle motion characteristic in the rotary kiln. The software Fluent is used to solve the Euler–Euler model. It is mentioned earlier that the rolling bed mode, which is employed in most kiln operations, comprises two distinct regions. In this paper, we focus on the rolling regime that is common for mixing purposes. The model predictions are verified by comparing with the published experimental data of Ding et al. [16]. The result, a three-dimensional rotary kiln model with an inclined angle, significantly improves the ability to simulate conditions within the bed without the necessity of rigorously accounting for the complex heat transfer and combustion phenomena of the freeboard.

2. Model description

2.1. Model outline

In terms of theoretical analysis, the structure of particle bed in rotating drums operated in a rolling mode has been observed by using several techniques. The parameters of the model are obtained from pilot kiln trials (5.5 m laboratory kiln). Shown in Fig. 1 is a schematic diagram of the structure constructed from experiment [17]. The rolling regime is characterized by two distinct regions, that is, a flowing surface layer and a fixed bed rotating at the angular velocity of the kiln. The active layer is dilated and the particles are in motion relative to each other. Upon reaching the surface, particles roll downward and rejoin the passive layer. Within the passive layer, the bed is closely packed and the particles rotate with the rotary kiln at fixed radius; this is plug-flow and there is little opportunity for particle interaction.

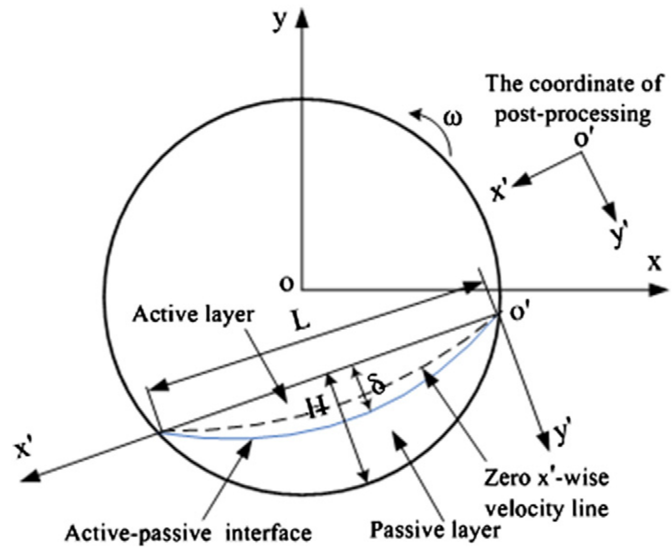

Fig. 1. Schematic diagram of a kiln operated in a rolling mode.

A Cartesian coordinate using in this paper is introduced in Fig. 1. The origin of two dimensional Cartesian coordinate is located on the center of the transverse section. In Fig. 1, the symbols δ, L and H denote respectively, the depth of the active zone, the full chord and the maximum depth of the bed.

The principle assumptions necessary to model the three-dimensional flow are limited to the following:

(a) Particles are cohesionless, mono-sized, spherical, rigid, and slightly inelastic.
(b) The particle ensemble behaves as a continuum.
(c) The granular particle bed is incompressible and bulk density is constant.
(d) The gas is incompressible and the density, the viscosity of the gas is constant.
(e) Mass transfer due to diffusion is negligible.

2.2. Governing equations of two-fluid model

2.2.1. Continuity equations

The continuity equations for the gas phase and the solid phase are as follows:

$$\frac{\partial}{\partial t}\left(\varepsilon_g\rho_g\right) + \nabla\cdot\left(\varepsilon_g\rho_g\nu_g\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s) + \nabla\cdot(\varepsilon_s\rho_s\nu_s) = 0 \tag{2}$$

$$\varepsilon_g + \varepsilon_s = 1 \tag{3}$$

where, ε is the volume fraction, ρ is the density and ν is velocity. The subscripts of s and g represent the solid phase and gas phase, respectively.

2.2.2. Momentum equations

The momentum equations for gas phase and solid phase are written as [18–21]:

$$\frac{\partial}{\partial t}\left(\varepsilon_g\rho_g\nu_g\right) + \nabla\cdot\left(\varepsilon_g\rho_g\nu_g\nu_g\right) = -\varepsilon_g\nabla P_g + \varepsilon_g\rho_g g - \beta_{gs}\left(\nu_g - \nu_s\right) + \nabla\cdot\left(\varepsilon_g\tau_g\right) \tag{4}$$