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Numerical simulation of particle motion and heat transfer in a rotary kiln

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ABSTRACT

A two-fluid approach and diverse heat transfer models are applied to a two-dimensional cross-section of a rotary kiln coupled with granular flow kinetic theory, which treats random granular motion as thermal molecular motion. The models are validated by comparison with the available experimental data. The results show that the bed surface velocity characteristic peak is located at the center and down the edges. The highest temperature is found at the bed surface and the temperature gradient in the bed is lower than that in the rotary kiln wall. The main factors that affect the temperature distribution are the initial gas temperature and rotational speed of the kiln.

1. Introduction

Rotary kilns are extensively used for cement, metallurgy, chemicals and in other industries because of their efficient mixing performance and heat transfer capacity [1]. Problems with material motion and heat transfer have been studied to improve particle mixing and decrease the time spent in the kiln so that production can be increased [2,3]. Some studies have concentrated on the mixing mode [4–6], and others on heat transfer [7–9]. Previous studies have shown that particle mixing plays a crucial role in the improvement of heat transfer in the kiln, but the mechanisms of heat transfer coupled with particle mixing in a cross-section are still unclear.

In general, the modes of particle mixing dynamics can be categorized into six forms: slipping, slumping, rolling, cascading, cataracting, and centrifuging [10]. These modes are dependent on kiln diameter and rotational speed, and particle properties and filling rate. Industrial rotating kilns are usually operated in a rolling and cascading mode at high temperatures. For both rolling and cascading modes, the bed material particles can be divided into active and passive regions [11,12]. The active region is dilated, and the particles are in motion relative to each other. The particles in the active region can absorb heat directly from bulk gas. Within the passive region, the bed is closely packed, and the particles rotate with the rotary kiln at a fixed radius, so there is little opportunity for interaction between the particles. Many studies have investigated the performance of the rotary drum mixture at atmospheric temperatures [13–15]. Simulations have also provided detailed two-dimensional [16] and three-dimensional [17] mixing characteristics without heat transfer.

Three heat transfer mechanisms—radiation, convection, and conduction—have been suggested for the rolling mode. Analysis of conduction in the particle bed and rotary wall has been limited to one-dimensional studies [12]. The inner wall of the rotary kiln has intermittent contact with the hot bulk gas and material. As the kiln rotates, the bulk gas transfers the heat directly to the exposed wall and particle bed through radiation and convection. Once covered by the particle bed, the rotary kiln wall transfers heat to the particle bed, forming a storage-release regenerative heat transfer in the mixing process. Meanwhile, some heat will be scattered to the environment due to the particle transport. Previous investigations of heat transfer in rotary kilns usually neglect the mixture performance.

Because the particle mixing and heat transfer characteristics are complex, measurement systems in rotary kilns remain limited. The heat transfer model is usually based on a large number of simplifying assumptions to build a one-dimensional mathematical model in axial coordinate or a two-dimensional heat transfer model in different cross-sections of the kiln. Agustini [18] performed a one-dimensional analysis to predict the effects of the rotary kiln diameter and angular velocity on the regenerative heat flow of the kiln wall. Schmidt [19] studied particle flow and heat transfer in a two-dimensional horizontal rotary kiln and found that the vortex generated by the gas increased the convection heat transfer at the top of the particle bed. Shi [8] investigated the heat transfer conditions in rotary kilns using a discrete element method/Computational Fluid Dynamics model.

As mentioned above, previous investigations have either focused on the mixing performance or on the heat transfer mechanism. However, the mixture performance in high-temperature conditions is still not

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Nomenclature

C_D	drag coefficient
c_p	heat capacity
d	particle diameter
D_e	equivalent diameter
D_{gs}	energy dissipation
e	restitution coefficient
Fr	Froud number
g	gravity
g_0	radial distribution
Gr	Grashof number
H	thickness of the particle bed
i	enthalpy
$\bar{I}$	unit tensor
J	radiosity
k	thermal conductivity
L	full chord of the bed
P	pressure
Pr	Prandtl number
Q	heat transfer rate
Re	Reynolds number
t	time
T	temperature
t_c	contact time of particle and kiln wall
v	velocity
v_s	actual velocity of particles
X	shape factor
y	distance of the location normal to the surface of the particle bed

Greek symbols

α	half of the filling angle
β	drag coefficient
γ_s	turbulent kinetic energy
ε	volume fraction
ζ	bulk viscosity
Θ	granular temperature
μ	shear viscosity
ρ	density
τ	viscous stress tensor
Φ	energy exchange between gas and particle
χ	experiment constant
ω	rotation speed of the kiln

Subscripts

a	air
b	bed
cd	rotary kiln wall
cw–cb	inner wall covered by the particles and particle bed
cw	covered wall and particles
ew	exposed wall
ew–eb	exposed inner wall and the particle bed
ew–ew	both the exposed inner walls
g	gas
g–eb	bulk gas and the particle bed
g–ew	gas and the exposed inner wall
p	particle
s	solid
os–en	outer wall and the environment
w	wall

well known. In this study, two-fluid flow theory and granular theory are coupled to simulate the mixture performance. The heat transfer model is also included in the simulations. The effects of the rotary speed, particle diameter, and bulk gas temperature on the temperature distribution are explored. The main goal of this work is to clarify the mechanisms of heat transfer coupled with particle motion in rotary kilns.

2. Physical and mathematical model

Two-fluid flow theory and granular flow kinetic theory are applied here to two-dimensional cross-sections in pilot kiln trials. Fig. 1 is a schematic of the cross-section of the kiln used in the experiments [20] and the present simulations. The origin of the two-dimensional Cartesian coordinates is located at the center of the cross-section. In Fig. 1, v_s is the actual velocity of particles and v_x' is the velocity parallel to the surface. For comparison with the results of [21], in the following sections of this paper, v_x' is calculated from the simulation results and treated as the particle velocity, and L denotes the full chord of the bed.

Particles in a rotary kiln with a rolling regime have local high fraction, so continuous flow can be assumed. Particles and gases are overlapping continuous phases.

The principle assumptions introduced for modeling the two-dimensional flow in this study are the following:

(a) The particles are spherical and rigid, have no cohesion, and are all of the same size.
(b) The particle ensemble behaves as a continuum.
(c) The granular particle bed is incompressible, and the particle density is constant.
(d) The gas is incompressible, and the density and viscosity of the gas are constant.
(e) Mass transfer due to diffusion is negligible.

2.1. Two-fluid model

Based on the continuum assumption, both solid and gas phases follow their sets of governing equations as follows:

2.1.1. Continuity equations

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

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g\right) + \nabla\left(\varepsilon_g \rho_g v_g\right) = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla(\varepsilon_s \rho_s v_s) = 0 \quad (2)$$

$$\varepsilon_g + \varepsilon_s = 1, \quad (3)$$

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

2.1.2. Momentum equations

The particles and gas flow move with the rotation of the kiln by viscous friction force. The main forces acting on the solid particles and gas are the viscous force, pressure and gravity. The viscous forces include viscous force between the particles and the inner wall, viscous force between the particles themselves, and viscous force between gas and particles. Therefore, accurate descriptions of the viscous force due to the viscosities are the keys to accurate simulation. In this research, granular temperature Θ is introduced as a variable parameter to describe viscosities which are given in Section 2.3 in detail.