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Granular flow characteristics and heat generation mechanisms in an agitating drum with sphere particles: Numerical modeling and experiments

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ABSTRACT

This work focuses on mechanism of heat generation in an agitating drum with dense gas-solid flow where particles move at high velocity (30 m/s). Numerical simulations and experiments are used to study the influence of granular flow characteristics, design parameters, process parameters and particle properties in heat generation and energy-conversion coefficient. Heat generates from sliding friction, rolling friction, viscous force of liquid-bridge or the modeled particle deformation. The variable goes to liquid volume due to high temperature (533 K) in wet particle flows. Concerning the velocity and particle motion several thermal transfer models are modified to match particle/particle and particle-wall/blade collisions, which are integrated to DEM-CFD numerical simulation. Experiments detected the temperature of external drum wall, the effect of temperature on liquid phase and the granular motion by visualization tests. The numerical results are verified by experimental data with good agreements. The effects of agitating speed and initial filling degree on temperature increase are not always in positive correlation, which are more significant in wet particles flow. Numerical simulations predicted the dynamic particles characteristic, the heat resources and the thermal conduction to reveal the heat generating mechanisms. Besides, the improved blades design to enhance heat generation is analyzed qualitatively and deduced.

1. Introduction

Agitated particle flows exist in various processing equipment as the mixer, heater and conveying devices [1–10] where energy input, transfer and dissipation are closely related to particle flow characteristics and equipment performances. And the energy dissipation caused by friction and particle deformation should not be overlooked especially, which can be applied to industrial production instead [11, 12].

In this work, a new method to heat particles only by agitating is studied with one motor, one agitating barrel and gas-gathering unit. It is not only convenient for transportation and installation but also for oil protection by evaporation under the boiling point especially in oily cuttings cleaning and oil sand exploitation.

Studies by experiments and numerical approaches to investigate the energy flow in particles flow are numerous. Nordstrom [13] studied the effect of kinetic friction force and static friction force on energy dissipation in grain particle flow by measuring the motion of particle experimentally. Burton [14] stated the energy dissipation in collisions between solid carbon dioxide particles. Sack [15] demonstrated the energy dissipation of particle flows in a vat vibrated in different modes. MacNamara [16] elaborated the energy input and dissipation by numerical approach. Kuang [17] touched the energy dissipation caused by friction in gas-solid flow field. However, the studies about the mechanism of heat generation in energy dissipation by friction and viscous force are relative few. Hou [18] referred to the energy dissipation of particles contact in his work about energy transfer in particle-fluid flow. Wang [19] investigated three forms of energy (collision energy, dissipated energy and maximum impact energy) in tumbling ball mills and predicted the evolution of product size with grinding time by DEM based models. McElroy [20] developed soft-sensor model for horizontal rotating drums that can quantitatively predict particle-particle impact energy within 5% of its actual value. Liu Chun [21] proposed and verified the energy conversion models with friction, viscous force and grain breakage. Nguyen [22] modeled the heat flow generated by friction and its transfer by conductance during the discharge of a silo.

DEM and DEM-CFD numerical approaches have been widely applied in the simulation of particle flow field, such as mixers [23–26], heaters [27, 28], particle conveying facilities [29, 30], reactors [31, 32], transmission pipelines [33] and ball mills [34]. The DEM-CFD numerical method was firstly applied to calculate heat transfer in gas-solid flows by Li et al.

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[35]. In the assumption of a flat circular contact, the approaches to model the particle-particle heat transfer have been developed for the short contact and long contact [36–38] and non-sphere and those particles whose Bi number is >0.1 [39, 40]. As for the dense gas-solid flow and the thermal conduction between particle and wall in the drum, numerical approach has been adopted in many reports [3, 41–45]. Xie et al. [3] numerically investigated heat transfer in a rotary drum mixer by coupling DEM with a conductive heat transfer model. Malone et al. [44] simulated the flow and heat transfer in large-particle liquid-fluidized beds with heated walls. Kwapinska et al. [45] calculated the heat of free-flowing particles by contacting with the rotary drum wall by means of the thermal version of DEM. Gui et al. [46] studied the heat conduction in wavy rotary drums and found they could speed up the heat transfer process especially at low rotating speeds. Macroscopic and microscopic models have been proposed to study heat transfer in rotating drums [1, 47–50]. Ding et al. [51] assessed heat transfer between wall and gas in drums operated in the rolling mode. Stuart et al. [52] modeled the heat and mass transfer in a well-mixed rotating drum. Chaudhuri et al. [53] studied the influence of rotation speed in temperature uniformity of the bed by simulating granular flows in rotary vessels. Shi et al. [54] simulated heat transfer in a rotary kiln by coupling DEM with CFD and investigated the effect of particle conductivities on heat transfer. Chaudhuri et al. [55] discovered the influence of lifter configuration (rectangular and L-shaped lifters) in heat transfer and flow of granular materials in a drum.

In conclusion, there are few works to investigate the mechanism of accelerating mechanical-thermal energy conversion caused by friction and viscous force in dynamic dry/wet particle flows. And few studies referred to the temperature distribution on wall. What's more, few studies are about wet particles which consider the volume of liquid as a variable. This paper selected the particle-particle/wall/blades heat transfer model in short collision, modified the liquid force models according to decrease liquid volume in experiments and modeled the partition coefficient to calculate the amount of frictional heat is transferred to particle, gas and wall/blades. These models were integrated to the DEM-CFD numerical simulation to calculate energy conversion, heat generation and thermal conduction in dry/wet particle flows. Wall and blades are considered as gather of numbers of cubic particles to study the temperature distribution on wall/blades. Meanwhile corresponding experiments were designed and conducted to verify numerical results. By analyzing the influences of agitating speed and initial filling degree in temperature increase, kinetic characteristic, collision characteristics and agitating drum design, this work tried to reveal the mechanism of heat generation in dry/wet particle flows and conclude the approaches in enhancing the heat generation and the energy conversion coefficient qualitatively.

The following assumptions are made in this work:

(1) The effect of contact force between liquid phase and solid particle on liquid phase evaporation is ignored;
(2) The liquid phase permeation is ignored;
(3) The influence of temperature in liquid viscosity is ignored.

2. Numerical model

In the study, the following changes are made in the existing relevant models and math formulas.

(1) The liquid volume is obtained from experiments (by detecting the vapor) and set as boundary conditions in the DEM-CFD simulations;
(2) Four kinds of heat resources are considered in the dissertation, and the thermal distribution of each resource is modeled and verified. In addition, the influence of high-speed gas in the thermal distribution in the barrel is taken into account.

2.1. Gas phase motion

The gas-particle thermal transfer was calculated by Navier-Strokes equations.

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

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g \mathbf{u_g}\right) + \nabla \cdot \left(\varepsilon_g \rho_g \mathbf{u_g} \mathbf{u_g}\right) = -\varepsilon_g \nabla p - \nabla \cdot \left(\varepsilon_g \tau_g\right) + S_p + \varepsilon_g \rho_g \mathbf{g} + \mathbf{F}_d \tag{2}$$

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g H_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g \mathbf{u_g} H_g\right) = -\nabla \cdot \left(\varepsilon_g k_g^{eff} \nabla T\right) + Q_p \tag{3}$$

where Q_p is the interphase energy transfer term, the interphase mass transfer is obtained by experiments where the mass and pressure of oil vapor are detected, and the data are applied to the CFD simulations as boundary conditions.

2.2. Governing equation of particle motion

In DEM simulations, the soft sphere contact model is adopted to describe particles motions. The contact, friction, liquid bride and gravitational force are dealt, and the liquid bridge force is only considered in wet particulate flows. The gas drag force on particles is neglected since it is seriously small compared with the contact force. The equations are listed.

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \mathbf{F}_{c,ij} + m_i \mathbf{g} + \sum_j \mathbf{F}_{lb,ij} \tag{4}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum \mathbf{T} = \left(\sum_j \mathbf{F}_{c,ij} + \sum_j \mathbf{F}_{lb,ij}\right) \times \mathbf{r}_{ij} \tag{5}$$

In the above formula, $m_i$is the particle mass, $\mathbf{F}_{c,\ ij}$and $\mathbf{F}_{lb,\ ij}$ the contact force and liquid bridge force between particle i and particle j or the wall. Here,$\mathbf{v}_i$,I_i,$\mathbf{T}$,$\boldsymbol{\omega}$are the particle translational velocity, the moment of inertia, the total torque acting on particle i and the rotational velocity. $m\mathbf{g}$ stands for the gravitational force on particle.

2.2.1. Contact force

The models to calculate the particle-particle interaction forces and torques have been deduced and summarized in the earlier works [18, 56–60] and the details can be obtained from these literatures.

(1) The normal force:

$$\mathbf{F}_{n,ij} = \mathbf{F}_{en,ij} + \mathbf{F}_{dn,ij} = -\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n} - \eta_n\left(6m^*E^*\sqrt{R^*\delta_n}\right)^{1/2}\mathbf{v}_{n,ij} \tag{6}$$

where the normal elastic force is calculated by $\mathbf{F}_{en,ij} = -\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}_{ij}$, and the normal damping force is given by $\mathbf{F}_{dn,ij} = -\eta_n(6m^*E^*\sqrt{R^*\delta_n})^{1/2}\mathbf{v}_{n,ij}$.

(2) In the tangential direction, the tangential force is calculated by

$$\mathbf{F}_{t,ij} = \ min\left[\left(\mathbf{F}_{et,ij} + \mathbf{F}_{et,ij}\right), -\mu_s\left|\mathbf{F}_{\mathrm{n},ij}\right|\mathbf{t}_{ij}\right] \tag{7}$$

where the tangential elastic force is $\mathbf{F}_{et,\ ij} = -\mu_s|\mathbf{F}_{en,\ ij}|(1-(1-\delta_t/\delta_{t,\ \max})^{3/2}\boldsymbol{\delta}_\mathbf{t}/|\boldsymbol{\delta}_\mathbf{t}|$, and the tangential damping force is $\mathbf{F}_{dt,ij} = -\eta_t (6\mu_s m^*|\mathbf{F}_{en,ij}|\sqrt{1-\delta_t/\delta_{t,\ \max}}/\delta_{t,\ \max})^{1/2}\mathbf{v}_{t,ij}$.

(3) And the rolling friction torque [18] is given by

$$\mathbf{T}_{r,ij} = \mu_{r,ij}\left|\mathbf{F}_{en,ij}\right|\boldsymbol{\omega}_{ij}^n / \left|\boldsymbol{\omega}_{ij}^n\right| \tag{8}$$