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DEM investigation of heat transfer in a drum mixer with lifters

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ABSTRACT

Rotating drums are widely used in industries to handle and process particulate materials and heat transfer is often involved in these processes. This work numerically investigated heat transfer inside a drum mixer by coupling the discrete element method (DEM) with a conductive heat transfer model. The mixer was fitted with different types of lifters and rotated at various speeds so their effects on heat transfer characterised by heat transfer coefficient (HTC) could be investigated. The simulation results showed that the specific HTC of the particle flow increased with increasing rotating speed but decreased with the number and height of the lifters. While all types of lifters sped up heat transfer, the straight lifers were more efficient than the arc shape lifters. To better understand the mechanisms of heat transfer, the specific HTC was linked to the particle-wall contact area and dynamic behaviour of particles. The change of lifter configuration, i.e. lifter height, number and shape, mainly affected the particle-wall contact area while the change of mixer rotating speed affected particle mixing behaviour.

1. Introduction

Rotating drums are widely used in industries for handling and processing granular materials, such as mixing, drying, granulation and coating [1]. Due to its simplicity, rotating drums are also suitable for studying complex behaviour of particles such as avalanche, mixing and segregation [2]. There have been considerable studies to understand the dynamics of particles and associated phenomena [3–6].

Heat transfer is often involved and plays a significant role in these processes. For example, in the coating process the solidification of coating solution on particle surfaces is significantly influenced by heat transfer. Sunkara et al. [7] investigated heat transfer in a rotating cylinder and observed faster heat transfer with increasing rotation speed. Herz et al. [8,9] experimentally studied the contact heat transfer between covered inner wall surface and solid bed in an indirectly heated rotary drum. They observed that the contact heat transfer coefficient increased with higher rotation speeds, lower filling levels and larger particle sizes. The thermos-physical properties of the solid bed also showed significant influence on the contact heat transfer with particles of larger density, conductivity and lower heat capacity having larger contact heat transfer coefficients.

Models at different levels have been developed to predict heat transfer in rotating drums. At the macroscopic level, Boateng et al. [10] developed a quasi-3D model to analyse heat transfer from freeboard gas to a packed bed in a rotary kiln and to predict the temperature distribution within the granular bed. Ding et al. [11] assessed heat transfer in drums operated in the rolling mode and observed that heat was mainly transferred from the drum wall to the bed while the heat transferred from the gas to the exposed surface of the bed was minimum. Stuart et al. [12] presented a mathematical model to characterise heat and mass transfer in a well-mixed rotating drum. Piton et al. [13] investigated a flighted rotary kiln and established a coupled thermal-granular model in which the fully heat transfer phenomena in an elementary volume along the kiln was considered.

At the microscopic scale, models based on the discrete element method (DEM) have been developed. Chaudhuri et al. [14] simulated particle flow in rotary vessels and investigated the effect of rotation speed on heat transfer and temperature uniformity of the bed. Shi et al. [15] coupled the DEM with CFD to simulate heat transfer in a rotary kiln. They found that heat transfer was dominated by gas-solid conduction at low particle conductivities and by solid-solid conduction at high particle conductivities. Figueroa et al. [16] examined the interplay between transient heat transfer and particle mixing in rotating tumblers and discovered that increasing mixing rate can be detrimental or favourable to the heating of the granular bed depending on the limiting step in the heat transfer process. Heat transfer is also affected by the configuration and operation of the drum. Chaudhuri et al. [17] studied the effect of lifter configuration (rectangular and L-shaped lifters) in a drum on the flow and heat transfer of granular materials. Gui et al. [18] studied the heat conduction in wavy rotary drums and found the wavy drums could enhance and speed up the heat transfer process especially under low rotating speeds.

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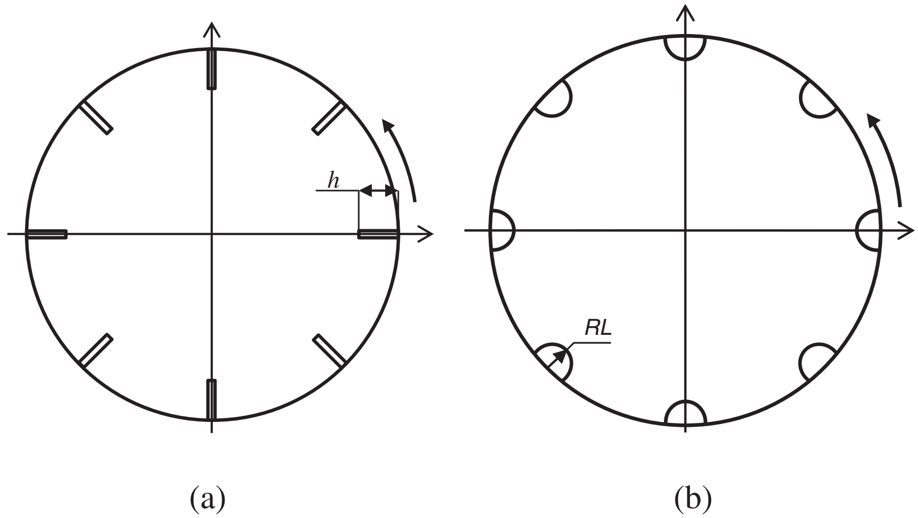

Fig. 1. Schematic diagrams of the drums with: (a) straight lifters, and (b) arc lifters.

Heat transfer inside a drum generally involves multiple physical factors such as particle-wall contact surface as well as particle dynamics. Changes to drum configuration and operation condition affect both particle-wall contact surface and particle behaviour. For example, increasing lifters increase particle-lifter contact surface but also affect particle-wall contact period and particle mixing in the radial and axial directions [19]. Exactly how they are affected and what is their relative importance, however, are less clear. The present study will model heat transfer in a drum mixer by combing DEM with a conductive heat transfer model, focusing on the effects of lifters (lifter size, number and shape) and operation variables (rotating speed). The aim is to better understand the mechanisms of heat transfer under different conditions so the optimal condition for the best heat transfer performance can be observed.

2. Numerical model description

2.1. DEM model

The DEM model has been used in the previous studies [20,21] and is summarised here. For each particle i with radius r_i and mass m_i, it has two kinds of motions, translational motion and rotational motion, which can be described as:

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \left(\mathbf{F}^{\mathrm{N}} + \mathbf{F}^{\mathrm{T}} + m_i \boldsymbol{g} \right) \tag{1}$$

Table 1
Parameters used in the simulations.

Parameter (unit)	Base value (range)
Number of particles, N_p	10,000
Particle diameter, d_p (mm)	2.0
Particle density, ρ (kg/m^3)	8900
Young's modulus, Y (Pa)	1.0×10^7
Poisson's ratio, γ	0.29
Particle specific heat capacity, C_p (J/kgK)	172
Particle thermal conductivity, K_p (W/mK)	385
Particle initial temperature, T_0 (K)	298
Drum wall temperature, T_w (K)	698
Drum Diameter × Length, $D \times L$ (mm × mm)	120 × 20
Lifter thickness, w (mm)	1
Lifter height, h (mm)	8 (4–12)
Number of lifters, N_L	10 (6–15)
Drum rotating speed, ω (rpm)	20 (5–40)

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j \left(\boldsymbol{R}_i \times \mathbf{F}^{\mathrm{T}} - \mu_r R_i \left| \mathbf{F}_{\boldsymbol{c}}^{\mathrm{N}} \right| \hat{\boldsymbol{\omega}} \right) \tag{2}$$

where $\mathbf{v}_i$, $\boldsymbol{\omega}_i$ are the translational velocity and angular velocity of the particle i, m_i and I_i are the mass and momentum of inertia of particle i. $\mathbf{F}^{\mathrm{N}}$and $\mathbf{F}^{\mathrm{T}}$ are respectively the normal and tangential forces on the particle i, given by [22]:

$$\mathbf{F}^{\mathrm{N}} = \frac{2}{3} E \sqrt{R^*} (\delta_n)^{\frac{3}{2}} \mathbf{n_c} - C_n E R^* \delta_n \cdot (\mathbf{v}_c \cdot \mathbf{n}_c) \mathbf{n}_c \tag{3}$$

$$\mathbf{F}^{\mathrm{T}} = -\mathrm{sgn}(\delta_t) \mu_s \left| \mathbf{F}_{\boldsymbol{c}}^{\mathrm{N}} \right| \left(1 - \left(1 - \frac{\min(\delta_t \ \delta_{t,max})}{\delta_{t,max}} \right)^{\frac{3}{2}} \right) \hat{\delta}_t \tag{4}$$

where $E = Y/(1-\gamma^2)$, Y and γ are Young's modulus and Poisson's ratio of the particle, respectively. m^* and R^* are, respectively, the equivalent mass and geometrical mean radius. δ_n, δ_t, and $\delta_{t,\max}$ are, respectively, the normal, tangential and maximum tangential displacements. $\mathbf{v}_c$ is the relative velocity of the two particles at the contact point. $\mathbf{n_c}$ is the unit vector at the contact point running between the centres of particles i and j. C_n, μ_s and μ_r are, respectively, the coefficients of normal damping, siding friction and rolling friction.

2.2. Heat transfer model

The heat transfer model previously developed to simulate fluidised beds [23,24] was adopted in the current work. The model has been demonstrated to be able generate results comparable to experimental measurement. This work, however, only considered conductive heat transfer through particle-wall and particle-particle contacts. The convective heat transfer was ignored as the fluid inside the drum was stagnant air and the rate of convective heat transfer was much slower than the rate of conduction [25]. Also as the maximum temperature in the system was at around 698 K, the thermal radiation was ignored.

Various thermal conduction mechanisms between particles have been identified [26], including particle-particle contact conduction and conduction through the stagnant fluid between the contact points of particles. However, the ratio of solid and fluid (air) conductivities in the current study is higher than 2000, the contribution from the stagnant fluid can be ignored. Thus, the particle-particle and particle-wall

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