Effects of Straight Lifters on Heating and Mixing Processes in Rotating Drums

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Citation

Abstract
In this work, the discrete element method (DEM) is applied to investigate the heating and mixing processes in rotating drums which are prevalently introduced to deal with particulate materials in many industries. Rather than conventional hollow drums, the drums with straight lifters are systematically analyzed. A normalized heat transfer coefficient (HTC) has been used to describe heat transfer performance. And a mixing rate based on Lacey mixing index has been employed to represent mixing process. Through simulations, it is found that both operational conditions and structural parameters affect significantly the drum’s performance. Increasing rotating speeds could remarkably promote the heat transfer process as well as the mixing in the granular bed. Comparing with lifter number, the rising lifter height has better enhancement on the heating and mixing. Finally heat transfer mechanisms in the drums have been discussed. It is concluded that the heat transfer inside the particle flow is mainly affected by rotating speeds and changing lifter heights dominates the heat transfer due to particle-wall contact area.

1. Introduction

Rotary drums are widely used in many processes like mixing, heating and drying in industry to deal with granular materials, which are enormously processed, handled and stored, such as metal ores and other dry and wet chemicals [3]. A number of studies had been carried out to reveal the granular flow behaviors and related phenomena [6, 34, 14, 28, 7, 27].

The granular system inside rotary drums becomes very complicated when heat transfer involves because the heat transfer happens together and also interplays with other processes. In industrial applications, many running drums with heat transfer happening often stay in the rolling or cascading regimes where the mixing phenomenon exists remarkably [25]. It is important to get well understanding of both the heating and mixing. The studies focusing on this topic could roughly be classified: (i) by experiments [31, 22, 21, 20], (ii) by continuum approach [35, 2] and (iii) by discrete modelling techniques [10, 11, 4]. The discrete element method (DEM) is a typical discrete modelling technique and it is effective to explore both heating and mixing because of its large-scale computing and visualization techniques. For example, Gui, et al. [17, 18] had investigated mixing and heat conduction of granular particles in a rotating drum via DEM. It was found that increasing rotation speeds could augment the mixing.
Even though many efforts had been spent on the heat transfer in rotary drums, there are still some problems poorly understood such as internal heat transfer enhancing [15]. Most previous studies focused on hollow drums while non-conventional drums with various internal structures have not been paid full attention, which should have been because of their better processing efficiency [30, 24]. Only a few studies attached importance to non-conventional drums. For example, Gui, et al. [16, 15] had explored the mixing and heat conduction in rotating wavy drums which are found to enhance and speed up the heat conduction especially under low rotating speeds. It could be seen that the non-conventional rotary drums may have more outstanding performance than normal ones, which could be a way for efficiency enhancement.

On the other hand, drums with straight lifters are common used in practical applications due to the simplicity and easiness to make, however, there are still some problems unclear such as the effects of lifter parameters on heat transfer performance. Inspired by the above points, an in-house DEM code has been used in this work to study the drums with straight lifters systematically, which would be an important component of our knowledge for rotary drums. Figure 1 shows the schematic diagram of the drum.

![Figure 1. Schematic diagram of a drum installed 8 straight lifters with a height h.](image)

### 2. Model Description

#### 2.1. DEM Model

In a particle system, any individual particle is considered to be distinct. The particle interacts with other particles or its neighboring environment and its motion obeys the Newton’s Second law. For each particle $i$ with radius $r_i$ and mass $m_i$, it always has two kinds of motions, translational motion and rotational motion, which can be generally described as

$$\frac{d}{dt} m_i \vec{v}_i = \sum_j (F^N + F^T + m_i \vec{g})$$

(1)

$$\frac{d}{dt} I_{ii} = \sum_j (R_i \times F^T - \mu_r R_i |F^N| \omega_j)$$

(2)

where $\vec{v}_i$, $\omega_i$ are the translational velocity and angular velocity of particle $i$, $dt$ is time step, and $F^N$, $F^T$ are respectively the normal and tangential forces resulted in particle $i$. $F^N_{ii}$ is the contact part of normal forces. $I_i$ and $M_{ij}$ mean the momentum of inertia and torques acting on particle $i$. The simplified Hertz-Mindlin and Deresiewicz model, developed by Hertz [19] for normal and Mindlin, et al. [29] for tangential direction, is used in this work. With damping forces considered, the normal force $F^N$ and the tangential force $F^T$ are described by

$$F^N = \frac{4}{3} E^* \sqrt{R^*} (\delta_n)^3 n_c - 2.0 C_n E^* R^* \delta_n \cdot (\vec{v}_c \cdot n_c) n_c$$

(3)

$$F^T = -\text{sgn}(\delta_t) \mu_s |F^N| \left(1 - \left(1 - \frac{\min(\delta_t, \delta_{t,\max})}{\delta_{t,\max}}\right)^2\right)^\frac{1}{2} \delta_t + 2C_t \left(\frac{1.5 \mu_n m^* |\vec{v}_c^*| (1 - \frac{\delta_t}{\delta_{t,\max}})}{\delta_{t,\max}}\right)^\frac{1}{2} \cdot (\vec{v}_c \times n_c) \times n_c$$

(4)

where $m^*$, $R^*$ and $E^*$ are the equivalent mass, geometrical mean radius and equivalent Young’s modulus of particle $i$ and particle $j$ contacting with particle $i$. And $\delta_n$, $\delta_t$, $\delta_{t,\max}$ are respectively the normal deformation, tangential deformation and maximum tangential displacement beyond which the sliding occurs. $\vec{v}_c$ indicates the velocity of the contact point between particle $i$ and $j$. $n_c$ is the unit vector at the contacting point running from the mass center of particle $i$ to particle $j$. $C_n$, $C_t$, $\mu_s$ and $\mu_r$ are respectively the coefficients of normal damping, tangential damping, sliding friction and rolling friction.

#### 2.2. Heat Conduction Model

Heat transfer process in rotary drums have multiple mechanisms, including heat conduction between the boundary or wall and the granular bed in the drums, conduction between two contacting particles in the granular bed, convection between particles and fluid, convection among fluid and radiation [4, 18].

In this work some negligible mechanisms have been omitted. Firstly, the convective heat transfer between the fluid and the particles will not be considered because the fluid inside the drum is considered to be stagnant air and be with low thermal conductivity. Secondly, the radiation transfer has also been ignored since the maximum temperature in the system is lower than 500-600 degrees Celsius where the radiation is negligible [13, 12, 18, 8, 36]. Thirdly, the thermal conduction through the interstitial gas is also neglected because the conductivity ratio of gas to particle [32] for this work is $\lambda_p/\lambda_{air} \approx 1.5e4 \gg 1$. Lastly, the conduction inside a particle is assumed to be transient due to the small Biot number of particles, i.e. $Bi = k_e/k_s \ll 1$, where $k_e$ and $k_s$ are respectively the thermal conductance inside the particles and between the particles.

The dominating conduction model is the one proposed by Batchelor et al. [1] and modified by Cheng et al. [5], which is shown as

$$Q_{ij} = 4r_c (T_j - T_i)/(1/k_{pi} + 1/k_{pj})$$

(5)

where $Q_{ij}$ represents the heat flux between particle $i$ and
particle $j$, whose temperatures are given by $T_i$ and $T_j$ respectively. $r_c$ means the contact radius of the contact area and it will be obtained from DEM simulation. $k_{pi}$, $k_{pj}$ are the thermal conductivities of particle $i$ and particle $j$ respectively.

After obtaining the various heat fluxes described above, the temperature of particle $i$ will change by the law which is given by

$$\frac{dT_i}{dt} = \frac{Q_i}{C_{pi}m_i} \quad (6)$$

where $C_{pi}$ is the specific heat of particle $i$. In each time step $dt$, particle $i$ will interact with another multiple particles and have a total heat flux $Q_i$.

### 2.3. Simulation Conditions

A horizontal rotary drum with two frictionless and adiabatic side walls, which is set deliberately to minimize the effects of the drum size [4], keeps static at the beginning. And then 10000 copper particles initially located in the central hollow room start to sink in the bottom of the drum under gravity. The drum will rotate at a given speed after the particles reach mechanical equilibrium. The lifters have the same temperature with the drum’s curve wall. The simulation conditions are concisely listed in Table 1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle number</td>
<td>$N_p$</td>
<td>10000</td>
</tr>
<tr>
<td>Particle diameter</td>
<td>$d_p$</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Particle density</td>
<td>$\rho$</td>
<td>8900 Kg/m$^3$</td>
</tr>
<tr>
<td>Particle specific heat</td>
<td>$C_p$</td>
<td>172 J/Kg/K</td>
</tr>
<tr>
<td>Particle thermal conductivity</td>
<td>$K_p$</td>
<td>385 W/m/K</td>
</tr>
<tr>
<td>Particle initial temperature</td>
<td>$T_0$</td>
<td>298 K</td>
</tr>
<tr>
<td>Drum wall temperature</td>
<td>$T_w$</td>
<td>698 K</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>1.0X10$^7$ Pa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\gamma$</td>
<td>0.29</td>
</tr>
<tr>
<td>Time step</td>
<td>$\Delta t$</td>
<td>2.8X10$^{-5}$ s</td>
</tr>
<tr>
<td>Drum diameter</td>
<td>$D$</td>
<td>120 mm</td>
</tr>
<tr>
<td>Drum length</td>
<td>$L$</td>
<td>20 mm</td>
</tr>
<tr>
<td>Drum rotating speed</td>
<td>$n$</td>
<td>20 (10-40) rpm</td>
</tr>
<tr>
<td>Lifter number</td>
<td>$NL$</td>
<td>10 (8-12) mm</td>
</tr>
<tr>
<td>Lifter height</td>
<td>$h$</td>
<td>8 (4-12) mm</td>
</tr>
</tbody>
</table>

### 2.4. Heating and Mixing Treatment

Firstly an equation has been derived based on Newton’s law of cooling to describe the average temperature of the granular bed, $T$. And it is shown as

$$T = T_w - (T_w - T_0) \times \exp\left(-\frac{h_0 A}{C_p m} \times t\right) \quad (7)$$

where $T_w$ and $T_0$ are respectively the temperature of the drum wall and the initial temperature of the granular bed. $h_0$ is the effective heat transfer coefficient of the granular bed. $m$ and $C_p$ are the mass and the specific heat of the granular materials. $A$ is the total contact area between the particles and the walls and lifters and it could be precisely calculated based on DEM statistics. Then the normalized effective heat transfer coefficient $h_e$ is available to describe the heating performance in the system.

On the other hand, the mixing process in radial direction that may be affected significantly by inside structures of the drum is focused. The mixing extent of granular matters could be quantitatively described by the Lacey mixing index [23] $M$ shown as

$$M(t) \equiv a + be^{-kt} \quad (9)$$

where $a$ and $b$ are two correlated parameters and have a relationship with the final mixing index. $k$ is called mixing rate and used to describe the mixing speed in the system.

### 3. Results and Discussions

The model validation has been omitted since the current models have been validated and applied [4]. Note even through our former study, from which some results are cited, has compared the heat transfer process in drum mixer with different lifters [33], in present work the effects of straight lifters on both heating and mixing are focused.

#### 3.1. Effect of Rotating Speed

Rotating speed has been explored in this section. Figure 2 shows the heating and mixing patterns in drums with same straight lifters (lifter height $h = 4dp$, width $b = 0.5dp$) in different rotational speeds from 10 to 40rpm. Note since the heat transfer route is radial, two types of particles, red and blue, are initially distributed in corresponding different radial positions [9]. The red particles are set to occupy inside a concentric circle with a radius equaling to 0.7 times of the drum radius (trying to equal the volumes), i.e. $r = 0.7R$. Therefore, the final mixing index [26] may not be 1.0. The granular bed reaches to maximum surface angle and then decrease immediately until the dynamic repose angle keeps steady.

It can be seen that the flow patterns have no big differences except that there are more particles thrown up in the air due to a faster rotation speed. Figure 3 gives good fittings of average granular temperatures and mixing indexes by Eq. 7 and Eq. 9 respectively. Both the heating and mixing processes have been enhanced by increasing rotating speeds. And then the normalized $h_0$ (note the unit is W/K per particle surface area) and the mixing rate $k$ could be obtained and shown in Figure 4, which demonstrates more clearly the effects on heating and mixing performance.
Figure 2. Axial snapshots of heat transfer (top) and mixing (bottom) patterns at t=3.0 s in a drum rotating at (a,d) 10 rpm, (b,e) 25 rpm and (c,f) 40 rpm.

Figure 3. The fitting of the average granular temperatures from Eq. 7 (a) and the fitting of the mixing indexes from Eq. 9 (b).

Figure 4. Variation of HTCs with speed (a) and variation of mixing rates with speed (b).
3.2. Effect of Lifter Height and Number

The size of straight lifters includes lifter height $h$ and lifter width $b$. Simulations show that the lifter width does not have the significant effects as the lifter height. Therefore the lifter width keeps constant, $0.5 \, dp$ in all simulations. Figure 5 gives the heating and mixing patterns. The heat transfer process also runs from the hot boundary to the core of the cold granular bed, which emerges a rough radial conductive transport procedure [4]. The lifters have slightly changed the isothermals of particles from concentric rings to curve ones on account of the long lifters with high temperature inserting in the granular bed. The evolution of HTCs of different lifter heights in the granular bed is plotted in Figure 6a. It could be found that the rising lifter height could increase the heating process to some extent. Figure 6b plots the variation of mixing rates. The higher the lifters are, the faster the mixing is.

Drums with different number of lifters have also been simulated. Figure 7a gives the heating and mixing patterns in drums with 8, 10 and 12 lifters. Reasonably and as expected, the cold core of the granular bed shrinks faster with increasing straight lifters because the more lifters result in larger heat transfer area. However, the rising lifter number seems to decrease the HTC (Figure 7b) which is also shown in our previous work [33]. For the mixing rate, no significant changes have been found in the simulated range. It is probably because the rotating speed is relatively low and the influence of the lifters is not remarkable yet.
3.3. Heat Transfer Mechanisms

The heat transfer process has two stages, one from wall (including curve wall and lifters) to particle bed and the other inside the particle bed, which are mainly affected by particle-wall contact area and particle mixing respectively. And it is necessary to understand which mechanism is dominant under different circumstances.

At first, it is found that the mixing rate increases by 113.7% when the rotating speed changes from 10rpm to 40rpm (Figure 4b) while the HTC rises by 20.7% (Figure 4a). And the mixing rate increases by 14.8% when lifter height changes from 4mm to 12mm (Figure 6a) while the HTC increases by almost the same percentage when the lifter changes from 4mm to 12mm (Figure 6b). Figure 8 shows clearly the comparison of effects on heating and mixing between different rotating speeds and lifter heights. The fitting line is \( h_u = 8.54k + 7.27 \) for different rotating speeds and \( h_u = 29k + 0.95 \) for different lifter heights.

![Figure 8](image)

Correlations of mixing rates and HTCs. The dash-dot-dot fitting line is \( h_u = 8.54k + 7.27 \) for different rotating speeds (10-40rpm) and the dash fitting line is \( h_u = 29k + 0.95 \) for different lifter heights (4mm-12mm).

On the other hand, statistics of contact areas in all simulations have been studied and it is found that the total contact area increases significantly when lifter height changes (shown in Table 2). However, the increasing rotating speed does not have an important influence to the total contact area.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Contact areas (unit: particle surface area)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum speed</td>
<td></td>
<td>with wall</td>
<td>with lifters</td>
</tr>
<tr>
<td>(rpm)</td>
<td>10</td>
<td>1.128</td>
<td>0.385</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.120</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>1.122</td>
<td>0.433</td>
</tr>
<tr>
<td>Lifter height</td>
<td>2</td>
<td>1.123</td>
<td>0.236</td>
</tr>
<tr>
<td>(dp)</td>
<td>4</td>
<td>1.120</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.119</td>
<td>0.563</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.142</td>
<td>0.244</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.096</td>
<td>0.611</td>
</tr>
</tbody>
</table>

Therefore, it could be summarized that the heat transfer change resulted from the lifter height (or lifter number) comes mainly from the particle-wall heat transfer mechanism. And the particle flow mechanism is dominant in the heat transfer enhancement resulted from the rising rotating speeds.

4. Conclusions

In this work, the DEM has been adopted to simulate the heating and mixing processes within the granular bed in rotary drums with straight lifters. The normalized HTC and mixing rate have been used to quantify the performance of heating and mixing. Based on the simulation results, it is found that the increase of rotary speed improves both heat transfer efficiency and mixing speed significantly. The lifter height could also enhance the heating and mixing processes while the lifter width does not show remarkable influence. The increasing lifter number seems to weaken the HTCs, however no prominent effects could be found on the mixing performance which is probably because the granular bed always stays in the rolling regimes. The mechanisms about heating and mixing in the drum has also been analyzed. It is concluded that the particle-wall heat transfer mechanism dominates when the lifter parameters change such as the lifter height and number while the heat transfer due to particle flow plays the major role under different rotating speeds.

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References


