Coupled CFD-DEM Simulation of Tea Particles in a Cylinder Fixation Equipment

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Abstract. This paper presents a coupled CFD-DEM approach to simulate the process of tea fixation in a cylinder fixation equipment. We have carried out quantitative assessments of process conditions, such as rotation speed, number and height of lifter and drum tilt. The temperature and movement characteristic of particles in the drum are obtained and analyzed. We assess the performance of our framework by employing temperature rising rate, which presents the efficiency of heat transfer between hot air and particles. An orthogonal experiment with four factors and three levels was designed, and the results show that the rotation speed and drum tilt have great influence on the temperature rising rate of tea particles, and the number and the height of lifter had little influence on the temperature rising rate. Finally, we have identified a lifter of 14 pieces and 70 cm height, a rotation speed of 20 r/min and a drum tilt of 3 degrees as a set of optimal operating conditions.

Keywords. CFD-DEM, tea particle, fixation, temperature rising rate.

1. Introduction

As the first procedure of green tea processing, fixation plays an important role in quality of tea product in terms of flavor, taste and appearance, and it was operated by hand previously. In the recent years, with the increasing consumption of tea product, the tea fixation equipment is widely used to meet the demand, which has the advantages of high automation, precision and yield. Due to the complexity of movement of tea particles in the equipment, the fixation could be influenced by many factors, such as hot-air temperature, tea grade and equipment parameters mostly. Understanding movement characteristics of tea particles and knowing how those factors influence these characteristics are important for the design, control and optimization of relevant industrial process. However, little effort has been made in studying the effect of factors on fixation, only several investigators have put their attention on the research in this respect.

Xu et al. analyzed the effect of helix rise angle of lifter on fixation based on the logarithm spiral line with the help of FLUENT software [1]. Polat et al. studied the effect of temperature and tea grade on the volatile substances on tea fixation [2]. Abhiram et al. studied the effect of pressure and feeding rate on the performance of orthodox roller fixation equipment [3]. However, the overall effect of equipment
parameters and the movement characteristics of tea particles were not taken into account from the above studies and remain unknown. A major obstacle in understanding the fixation process is the complex interactions between tea particles and fluid as well as those among tea particles.

Because the CFD has the function of simulating fluid, and the DEM has the function of simulating particle dynamics, the coupling of CFD and DEM can obtain characteristics of particles and fluid that was firstly reported by Tsuji et al. [4]. Many scholars have done relevant research in many fields such as fluidized bed and material drying. Ma et al. investigated the effect of aspect ratios on the fluidization of the rod-like particle by coupled CFD-DEM algorithm, and the results showed that particles with smaller aspect ratio can absorb more energy from fluid flow [5]. Sudbrock et al. analyzed the transient heat and mass transfer of beech wood and silica gel in mechanically agitated particle beds using coupled CFD-DEM simulations [6]. Scherer et al. analyzed the effect of baffle design on the convective drying of wood chips in a baffled laboratory rotary dryer with coupled CFD-DEM simulations [7]. Hence, the method of coupled CFD-DEM can be applied to simulate the process of tea fixation and analyse the effect of parameters of equipment on tea fixation.

In this paper, the fixation process in cylinder fixation equipment with hot-air pipe was simulated using coupled CFD-DEM. Because the main purpose of fixation is to make the temperature of fresh leaves rise rapidly using high temperature to inactivate the enzymes, so as to prevent the reddening of green tea leaves. Thus the temperature rising rate were regarded as an important statistic. The effects of rotation speed, drum tilt and number and height of lifter on this statistic are studied by designing orthogonal experiment with four factors and three levels. The optimal combination of factors may facilitate the design and optimization of tea fixation equipment and improve the quality of tea product.

2. Mathematical Modeling

2.1. Continuous fluid phase

The hydrodynamics of fluid phase in a CFD-DEM framework was numerically calculated by resolving the volume-averaged Navier–Stokes equations ((1) and (2)) including the momentum exchange with particulate phase. In order to take the presence of particulate phase into account, the porosity $\varepsilon$ was included.

$$\frac{\partial (\varepsilon_f \rho_f)}{\partial t} + \nabla \cdot (\varepsilon_f \rho_f v_f) = 0$$

(1)

$$\frac{\partial (\rho_f \varepsilon_f v_f)}{\partial t} + \nabla \cdot (\rho_f \varepsilon_f v_f v_f) = \varepsilon_f \nabla P + \nabla \cdot (\mu \varepsilon_f \nabla v) + \varepsilon_f \rho_f g - F_{pf}$$

(2)

where $\rho_f$, $P$, $v_f$, $t$, $\mu$, and $g$ are: fluid density, pressure, velocity, time, fluid viscous, and gravitational acceleration, respectively; $F_{pf}$ represents a momentum sink term that describes the momentum exchange due to the interaction between fluid phase and particulate phase, and it can be calculated from the drag force and buoyant force; $\varepsilon_f$ represents the volume fraction of the fluid and can be calculated as:

$$\varepsilon_f = 1 - \sum_{i=1}^{n} \frac{V_{p,i}}{V_{cell}}$$

(3)

where $V_{p,i}$ and $V_{cell}$ are the volume of particle $i$ and computational cell, respectively; $n$ represents the total number of particles in this computational cell.

The momentum sink term $F_{pf}^I$ can be represented as:

$$F_{pf}^I = \frac{1}{V_{cell}} \sum_{i=0}^{n} F_{pf,i}$$

(4)
where $V_{cell}$ is the volume of this computational cell; $n$ represents the total number of the particles in the cell; $F_{d,i}$ represents the drag force acting on particle $i$ in the cell.

2.2. Discrete particle phase

In the present study, the Discrete Element Model (DEM), firstly proposed by Cundall and Strack [8], is used to simulate the behaviors of particulate phase by calculating all forces and moments which cause the translational and angular motion of particles. According to Newton’s Laws of Motion, the translational motion of particle $i$ is calculated as:

$$m_i \frac{dv_i}{dt} = \sum_{j=1}^{n} F_{ij}^c + F_{ij}^f + F_{ij}^g$$

(5)

where $m_i$, $n$, $M_{i,j}$, $I_i$, $v_i$ and $w_i$ are the mass, number of total contacts, contact torque, moment of inertia, the translational and angular velocity, respectively; $F_{ij}^g$ represents the gravitational force; $F_{ij}^f$ represents the fluid interaction force acting on particle $i$; $F_{ij}^c$ represents the contact force acting on the particle $i$ from particle $j$.

In the present study, the Hertz-Mindlin(No Slip) contact model is employed to describe the particle contacts [9]. As shown in Fig. 1, there are springs and dampers respectively in the normal and tangential directions, and a slider in the tangential directions. Hence, the equation of contact force $F_{ij}^c$ is given as:

$$F_{ij}^c = \sum_{j=1}^{n} \left( F_{n,ij}^c + F_{t,ij}^c \right)$$

(6)

![Fig.1](image-url)

Fig.1 Normal displacement $\delta_{n,ij}$ and tangential displacement $\delta_{t,ij}$ of particle collision; (b) the contact model between two particles.

where $F_{n,ij}^c$ and $F_{t,ij}^c$ are respectively the normal contact force and tangential contact force and can be calculated as follows:

$$F_{n,ij}^c = \left( -k_n \delta_{n,ij}^{3/2} - \eta_n v_{ij} \cdot n_{ij} \right) n_{ij}$$

(7)

$$F_{t,ij}^c = \begin{cases} -k_t \delta_{t,ij} - \eta_t v_{t,ij} |F_{t,ij}^c| \leq \mu |F_{n,ij}^c| \\ -\mu |F_{n,ij}^c| |v_{t,ij}| |F_{t,ij}^c| > \mu |F_{n,ij}^c| \end{cases}$$

(8)

Where $n_{ij}$ is the unit vector directed from the center of particle $i$ to particle $j$; $v_{ij}$, $v_{t,ij}$ are the relative velocity and relative tangential velocity of particle $i$ and particle $j$, respectively; $\delta_{t,ij}$ and $\delta_{n,ij}$
are the normal and tangential displacements, respectively; $\mu$, $k_n$, $k_t$, $\eta_n$ and $\eta_t$ are the particle sliding friction coefficient, normal stiffness coefficient, tangential stiffness coefficient, normal damping coefficient and tangential damping coefficient, respectively.

The angular motion of particle $i$ is calculated as:

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n} T_{i,j} = \sum_{j=1}^{n} F_{i,j} \times \eta_{ij}$$

(9)

where $T_{i,j}$ is the torque; $I_i$ is the moment of inertia of the particle $i$ with radius $r_i$, given as $I_i = 0.4m_i r_i^2$. Note that $T_{i,j}$ is caused by the tangential force $F_{i,j}$ between particle $i$ and particle $j$. $\eta_{ij}$ has the magnitude of radius of particle $i$ and points from the center of particle $i$ to the contact point.

2.3. Fluid-particle interaction

Interaction forces between fluid phase and particulate phase include both drag force and buoyant force. However, in the present study it is assumed that the effect of drag force outweighs buoyant force and hence buoyant force can be ignored.

Considering the drag force is influenced by fluid and ambient particles, the Di Felice drag model has been employed in the present study \[10, 11\]. The equations for calculating the drag force are given as follows:

$$F_{d, f} = \frac{1}{2} A_{\perp} C_D \rho \frac{1}{2} |v_f - v_g| (v_f - v_g)$$

(10)

$$\chi = 3.7 - 0.65 \exp \left( \frac{(1.5 - \log_{10} Re_p)^2}{2} \right)$$

(11)

$$Re_p = \frac{\rho |v_f - v_g| d_p}{\mu}$$

(12)

$$C_D = \begin{cases} 24/Re_p & Re_p \leq 1 \\ (0.63 + 24/Re_p^{0.5})^2 & Re_p > 1 \end{cases}$$

(13)

where $C_D$, $v_f$ and $v_g$ are the drag coefficient, fluid velocity and particle velocity, respectively. Note that for spherical particle, $A_{\perp} = \pi d_p^2/4$, where $d_p$ is the diameter of the spherical particle. Whereas for non-spherical particle, $A_{\perp}$ is a variable which is related to the particle orientation and the velocity of the corresponding grid cell at every moment.

There are various modes of heat transfer in the process of tea fixation. However, the conductive heat transfer between particles was ignored as the particle diameter was so small that can be considered as an isothermal body due to its low Biot number. Also as the maximum temperature of hot air used in the present system was at around 573 K, the radiative heat transfer was ignored \[12\]. Therefore, only the heat transfer between particles and its local surrounding fluid were studied in this paper. The governing equation of energy balance for particle $i$ was written as \[13\]:

$$m_i c_{pi} \frac{dT_i}{dt} = Q_{L f}$$

(14)

where $m_i$, $c_{pi}$, $T_i$ and $Q_{L f}$ are the mass, specific heat capacity, temperature of particle $i$ and rate of conductive heat transfer between particle $i$ and fluid, respectively.
Since the computational resolution of heat transfer between fluid and particles was based on the time scale of particle, it was sufficiently accurate to assume that the temperature distribution inside particles is uniform. Therefore, the heat transfer rate \( Q_{i,f} \) can be calculated as follows [14, 15]:

\[
Q_{i,f} = h_{i,f} A_i (T_f - T_i)
\]

where \( A_i \) is the surface area of particle i; \( T_f \) and \( T_p \) are the temperature of fluid and particlei, respectively; \( h_{i,f} \) is the heat transfer coefficient, which is given as:

\[
h_{i,f} = \frac{\lambda_f N_u_i}{d_i}
\]

where \( \lambda_f \) is the thermal conductivity of fluid; \( d_i \) is the diameter of particle i; \( N_u_i \) is the Nusselt number, which can be evaluated by the classical correlation when the phase is dilute. However, the effect of surrounding particles cannot be ignored when the phase is dense. Therefore, in the present study a modified correlation proposed by Li & Mason was employed by relating \( N_u_i \) to the gas volume fraction \( \epsilon_f \), which was given as [15]:

\[
N_u_i = \begin{cases} 
2 + 0.6 \epsilon_f^3 Re_i^{1/2} Pr_i^{1/3} & \text{if } Re < 200 \\
2 + 0.5 \epsilon_f^3 Re_i^{1/2} Pr_i^{1/3} + 0.02 \epsilon_f^3 Re_i^{0.8} Pr_i^{1/3} & \text{if } 200 < Re < 1500 \\
2 + 0.000045 \epsilon_f^3 Re_i^{1.8} & \text{if } Re > 1500 
\end{cases}
\]

where \( Pr \) is the Prandtl number; \( Re \) is the Reynolds number of particle i; the exponent \( n = 3.5 \) is chosen in this paper.

3. Model Implementation

3.1. DEM model

The movement characteristics of tea particles were studied in the platform of DEM code EDEM 2.7. As shown in Fig. 2, the drum has a length of 4 m and a diameter of 1 m, and it is fitted with lifters which were evenly distributed on the drum inwall. The simulation geometry of equipment is illustrated in Fig. 3. In the simulation, particles were initially generated randomly and allowed to fall under the gravity into the drum inwall. Meanwhile, the hot air was discharged into the drum to activate the heat transfer model. As the principle
3.2. **CFD modeling**

The SIMPLEC method, transient-in-time solver and pressure-based style were adopted to solve the governing equations of fluid phase in the platform of CFD software ANSYS Fluent 15.0. The $k-\varepsilon$ turbulence model with the Standard Wall Functions for near-wall treatment were used. The boundary conditions of pressure-outlet and velocity-inlet were used. The parameters of fluid were listed in Table II.

3.3. **CFD-DEM coupling**

The coupled CFD-DEM framework was implemented by User-Defined Function (UDF) to simulate the interaction between fluid and particle. Fig. 4 shows the calculation procedure of parallel coupled CFD-DEM algorithm based on the domain decomposition in FLUENT. According to the suggestions of Ting and Corkum, the time step in EDEM was set smaller than that in Fluent [16]. To ensure the stability and accuracy, the time steps set in CFD model and DEM model were $10^{-5}$ and $10^{-7}$, respectively. At each time step, besides position and velocity, the temperature and size of particles were calculated to obtain the porosity, volumetric source term and heat transfer rate in each computational cell.

| Parameters of equipment | Value               |
|-------------------------|---------------------|
| Material                | steel               |
| Lifter height, $h$(mm)  | 60, 70, 80          |
| Number of lifters, $N_L$| 10, 12, 14          |
| Drum rotating speed, $\omega$(r/min) | 15, 20, 25          |
| Drum inclination angle, $\alpha$(deg) | 2.5, 3, 3.5       |

| Parameters of fluid phase | Value |
|---------------------------|-------|
| Temperature (K)           | 593   |
| Pressure-outlet (Pa)      | 0     |
| Velocity-inlet (m/s)      | 6     |
Fig. 4 Calculation procedure of coupled CFD-DEM.

By transferring those information to the CFD cells, the pressure, velocity and temperature field of fluid phase were determined by solving the governing equation.

4. Result And Discussion

4.1. Effect of rotation speed
In this study, the rotation speeds of drum was varied from 14 to 26 r/min. Fig. 5 shows the evolutions of average temperatures of particles with different rotation speeds. Compared with the rotation speeds of 16 and 24 r/min, the average temperature increases faster at the rotation speeds of 20 r/min. This is due to the fact that particles are lifted more often within the same time span. On the other hand, the heat exchange between hot air and particles is also enhanced during the process of falling. Fig. 5 shows the dynamics and heat transfer patterns of particular phase at 12.0 s with different rotation speed. At the rotation speeds of 14 r/min, particles are lifted and then collide with the central pipe as they fall. At the rotation speeds of 20 and 26 r/min, the particles are lifted higher with increasing rotation speeds and then directly fall into the drum inwall without colliding with the central pipe. However, the particles are absorbed to the drum inwall by centrifugal force when the rotation speed is so high, resulting in the decrease of time consumed by falling. Because the heat transfer between hot air and particles is mainly carried out during the process of falling, thus the time consumed by heat exchange between hot air and particles is reduced, resulting in a slower temperature rising rate. Therefore, the rotating speed should be set properly to make sure that paricles will fall without colliding with the central air pipe and being absorbed to the drum inwall.

Fig. 5 Evolutions of the average temperatures of particles at different rotation speeds.
4.2. Effect of lifter configuration
The heat transfer between hot air and particles is also affected by the height (H) and number (N) of lifters, and the effects are presented here. Fig. 7 and Fig. 8 show the evolutions of average temperature of particles in the drum with different lifter height (H) and lifter number (N). In the simulated range from H=60 to H=80cm, the lifter with higher height can lift more particles during each lifting process. However, the temperature rising rate has no significant change. This is due to the fact that every time the number of particles lifted by different lifters remains unchanged under the condition that the total number of particles remains unchanged. In the simulated range from N=10 to N=14, it is observed that the temperature rising rate increases slightly with increasing lifter number. This is due to the fact that the cluster of particles is divided into more nubbles when the equipment has more lifter number, resulting in an improved dispersion degree of particles. It can be predicted that the
effect of lifter height and lifter number on the temperature rising rate will be greater when the number and size of particles are particularly large and should be further studied.

4.3. Effect of drum tilt
In this section, the effect of drum tilt on heat transfer is investigated. Fig. 9 shows the evolutions of average temperatures of particular phase with different drum tilt. In the simulated range from 2 to 4°, the temperature rising rate increases with increasing drum tilt. This is due to the fact that the displacement of particles along the axis of drum increases with increasing drum tilt during the process of falling, which leads to the longer time of heat exchange between hot air and particles. However, particles are lifted less frequently within the same time span, and it has a greater impact on the temperature rising rate. Therefore, the temperature rising rate decreases at the drum tilt of 4°.

4.4. Orthogonal experiment
In order to study the degree of effect of different factors on temperature rising rate, an orthogonal experiment with four factors and three levels is designed. The parameters are listed in Table III. It can be seen from the results (shown in Table IV and Fig. 10) that the changes to rotation speed and drum tilt can lead to greater changes in temperature rising rate. However, the changes to lifter number and lifter height has little effect on temperature rise rate. When A, B, C and D are chosen as level 2, level 3, level 2 and level 2, respectively, the highest temperature rising rate is achieved.

![Fig.9](image_url) Evolutions of the average temperatures of particles at different drum tilt.

![Fig.10](image_url) Comparison of range for different factors
### Tab.3 Parameters of orthogonal experiment

| Factors            | Levels | Symbol | 1  | 2  | 3  |
|--------------------|--------|--------|----|----|----|
| Rotation speed(r/min) | A      | 15     | 20 | 25 |
| Lifter number      | B      | 10     | 12 | 14 |
| Drum tilt(deg)     | C      | 2.5    | 3  | 3.5|
| Lifter height (cm) | D      | 60     | 70 | 80 |

### Tab.4 Results of orthogonal experiment

| Levels | A    | B    | C    | D    |
|--------|------|------|------|------|
| 1      | 5.22 | 5.12 | 4.94 | 5.02 |
| 2      | 5.23 | 5.06 | 5.43 | 5.18 |
| 3      | 4.90 | 5.17 | 4.98 | 5.14 |
| Range  | 0.33 | 0.11 | 0.45 | 0.16 |

### 5. Conclusion
We have formulated in this paper a comprehensively CFD-DEM numerical framework to study the heat transfer between hot air and tea particles in rotating drum of fixation equipment which was fitted with lifters. The temperature rising rate was adopted to characterise the efficiency of heat transfer. An orthogonal experiment was designed to investigate the effect of four factors on the temperature rising rate. The results showed that the effects of rotation speed and drum tilt on the temperature rising rate were greater than that of lifter height and lifter number. Further, the mechanism of effect was analysed and the parameters of factors should be chosen properly based on the simulation results. Due to the small size of particles, the small time step needed to calculate the particle movement and collisions between particles. It is expected that with the improvement of computer capabilities shorter running times will make the model used in this paper more applicable and allow us to gain better information regarding the fixation process of tea particles.

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