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Simulation investigation of drying characteristics of wet filamentous biomass particles in a rotary kiln

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ABSTRACT

Biomass is an important part of renewable energies and characterized by physical properties and structures, including high moisture content, heterogeneous size, and low density. Wet filamentous biomass particle drying was performed in a rotary kiln, aiming to get the appropriate moisture content. To investigate the drying characteristics of biomass particles, a mathematical model on the heat and mass transfer was proposed. Experiments with filamentous biomass particles under selected conditions were compared to simulations and the feasibility of mathematical models was verified. Furthermore, the transfer of heat and mass between the wet filamentous biomass particle and gas flow was described in terms of rotary drum temperatures, gas flow velocities and gas temperatures. The aim was to gain more information on temperature, moisture content, and the moisture evaporation rate of wet filamentous biomass particles within a rotary kiln during drying processes. The simulation results indicated that the drum temperature could greatly affect the drying behaviors of particles. The temperature and moisture content of particles were marginally affected by properties of the gas flow. The results show that the proposed models offer effective methods to investigate the drying characteristics of wet filamentous biomass particles.

1. Introduction

Biomass is an important part of renewable energies, which is characterized by physical properties and structures, including high moisture content, heterogeneous size and low density [1]. In order to obtain a higher energy value, biomass particles always need to be dried before combusting.

Several types of dryer are available for biomass heating and drying, rotary kilns are the most common and have low maintenance costs. Rotary kilns have been currently applied in a variety of industries, such as mineral, chemistry, fuel, and food. They have broad applications, involving the transfer of heat and mass between the gas phase and the solid phase. For instance, the pre-treatment of biomass particles and material conveying in industrial systems [2]. As the wet granular material, including biomass, food grains, tea leaves, and wood chips, moves through the rotating drum, wet particles are heated and internal moisture is released.

Particle-scale heat and mass transfer are the key points for grasping drying behaviors in the granular wet material. However, due to the difficulty in quantitatively measuring the temperature and moisture content of particles in drying processes, many studies have been conducted for wet particle heat and mass transfer by numerical methods [3]. These researches have been focused on the drying characteristics of a single biomass particle [4–6] and obtained details on the heat and mass transfer within the particle based on experimental apparatus. However, measurements on a single particle have been unavailable for industrial-scale drying equipment, such as a rotary kiln. A large number of wet biomass particles are conveyed in a rotary kiln and moisture is needed to be released during the actual drying process. Therefore, it is extremely difficult to directly detect the trajectory of particles and measure the temperature and moisture content inside.

Discrete Element Method (DEM) has been proposed to track motion and force of a particle, especially for studying complex non-spherical particle dynamics in granular biomass materials. Due to the improvement of the capability of a computer, CFD and DEM approaches have started to flourish and are used to resolve more industrial problems [7]. Numerous efforts show that DEM-CFD is a high potential method to investigate non-spherical particulate systems by capturing motion behaviors of particles. Recently, coupled DEM and CFD approach is developed to model heat and mass transfer in heterogeneous gas-solid two-phase systems [8]. Brosh and Levy [9] adopted a model to simulate heat transfer between particles and gas flow in a conveying pipe by

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DEM-CFD numerical code. Mehrabian [10] developed a one-dimensional model to resolve the thermal conversion of thick biomass particles in a fuel bed. The model could be used to calculate the temperature of particle phase and gas phase and applied for spherical and cylindrical particles. Zhou and Yu [11] combined discrete particle simulation and CFD to study the heat transfer of particle-particle and particle-fluid in packed and bubbling fluidized beds at the particle scale. Peng [12] found that if the ratio of computational cell size to particle size larger than 3.82, the simulation was stable and the results of prediction were more accuracy.

Therefore, one can see that the heat and mass transfer between wet filamentous biomass particles and conveying gas flow has been a recurring subject of the research. In this article, a model on motion behaviors of the filamentous biomass particle system has been developed by DEM and the details on the mean residence time of biomass particles are obtained. The heat and mass transfer model is employed to investigate drying characteristics of wet filamentous biomass particles within a rotary kiln. Temperature and moisture content have been discussed under a series of numerical conditions, including the velocity of gas flow, the temperature of rotary drum and gas flow.

2. Methods and modeling

2.1. Particle motion model

It costs a huge computational time in order to investigate large/industrial-scale particulate systems. Especially for a multi-phase flow system, including non-spherical particles and fluid, the computational effort has been heavily increased. However, the limitation of the non-spherical particle number is $< 10^4$ by DEM [7,13].

Motion behaviors of biomass particles in the rotary drum have a significant impact on the performance of drying systems and quality of the dried material. Thus, it is necessary to develop an appropriate model on motion characteristics of particles before studying the drying characteristics of wet biomass particles. In this paper, the Eulerian method was employed for the gas phase and Lagrange method for the particle phase.

2.1.1. Particle phase-gas phase

In this work, the motion behaviors of filamentous biomass particles were described based on the DEM. The total force that acting on a particle consists of a gravitational force, fluid forces, as well as collision contact forces. Therefore, the equations for a particle i are

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{f}_c + \boldsymbol{f}_{f,i} + m_i \boldsymbol{g} \tag{1}$$

$$\boldsymbol{I}_i \frac{d\boldsymbol{w}_i}{dt} = \boldsymbol{T}_i \tag{2}$$

In this study, the drag force was taken into account and treated as the fluid force. The collision contact force was solved based on a soft-sphere model, the details are presented in the following subsections. The drag force is described in terms of the drag coefficient under the steady-state condition and based on the relative velocity between gas flow and particle as [14].

$$F_D = \frac{1}{2} C_D A_p \rho_g \, |u_g - u_p| (u_g - u_p) \tag{3}$$

where F_D and C_D represent the drag force and the drag coefficient, respectively; C_D is a dimensionless number; A_p is the surface area of a particle and ρ_g is the density of gas flow; u_g and u_p are the velocities of gas flow and particle, respectively. The drag coefficient is always associated with a particle surface area and gas flow speed [15, 16]. Based on a large number of experiments and empirical formulas [17, 18], the drag coefficient C_D was a function of Reynolds number Re, as shown below

$$C_D = \begin{cases} \frac{24}{Re} & 0 < Re < 1 \\ \frac{10}{\sqrt{Re}} & 1 < Re < 500 \\ 0.44 & 500 < Re < 1500 \end{cases} \tag{4}$$

$$Re = \frac{|u_p - u_g| \, \rho d_{eq}}{\mu_g} \tag{5}$$

The drag coefficient, related to Reynolds number and particle velocity, can also be described [19] as

$$C_D = \left(0.63 + \frac{24}{5\sqrt{Re_p/u_{cp}}}\right)^2 \tag{6}$$

where d_{eq} is the diameter of a sphere with the same volume as the filamentous particle and μ_g represents the viscosity of gas flow. u_{cp} is the corrected velocity of the particle, which is described in terms of Reynolds number as

$$u_{cp} = 0.5(a - 0.06\,Re + \sqrt{(0.06\,Re)^2 + 0.12\,Re(2b - a) + a^2})^2 \tag{7}$$

$$a = a_g^{4.14}$$
$$b = \begin{cases} 0.8 a_g^{1.28} & a_g \le 0.85 \\ a_g^{2.65} & a_g > 0.85 \end{cases} \tag{8}$$

where a_g represents the ratio of the volume of gas to the total volume of gas and particles, including both gas phase and particle phase. $a_g + a_p$ is a constant of 1.

2.1.2. Particle-particle and particle-wall

Collisions of filamentous biomass particle to particle and particle to drum wall were taken into account since they could change the path of particles in a rotary kiln. However, due to the crimp properties of filamentous biomass particles, several filamentous biomass particles might be mixed and reunited into a spherical particle during the motion process. Then, the mixed spherical-like particles kept in the same motion behaviors until to the output end. Therefore, it was assumed that all filamentous biomass particles could be treated as several virtual spherical particles and these filamentous particles within a virtual particle kept in the same motion state. Based on the above assumptions, the limitation of the particle number in large/industrial-scale equipment could be resolved and the computational time was sharply reduced. In order to investigate collisions of virtual particles, the soft-sphere model was proposed to investigate collisions between particle and particle, as well as particle and boundary wall.

In this work, we assumed that collisions among virtual particles could last for a while at the collision point. The boundary wall was treated as a huge sphere when a collision between the particle and the wall occurred. Central collision and eccentric collision were taken into account in this model, as shown in Fig. 1.

The impact force between two virtual particles (particle i and particle j) can be described as

$$\boldsymbol{f}_{C,ij} = \boldsymbol{f}_{Cn,ij} + \boldsymbol{f}_{Ct,ij} \tag{9}$$

$$\boldsymbol{f}_{Cn,ij} = (-k_n \boldsymbol{\delta}_{n,ij} - \eta_n \boldsymbol{v}_{r,ij} \cdot \boldsymbol{n}_{ij}) \boldsymbol{n}_{ij} \tag{10}$$

$$\boldsymbol{f}_{Ct,i} = -k_t \boldsymbol{\delta}_{t,ij} - \eta_t \boldsymbol{v}_{s,ij} \tag{11}$$

$$\boldsymbol{v}_{s,ij} = \boldsymbol{v}_{r,ij} - (\boldsymbol{v}_{r,ij} \cdot \boldsymbol{n}) \boldsymbol{n} + r(\boldsymbol{\omega}_i + \boldsymbol{\omega}_j) \times \boldsymbol{n} \tag{12}$$

where $\boldsymbol{f}_{Cn,ij}$ and $\boldsymbol{f}_{Ct,ij}$ present contact forces in normal and tangential directions, respectively. $\boldsymbol{\delta}_{n,ij}$ and $\boldsymbol{\delta}_{t,ij}$ are the normal and tangential deflection of the two virtual particles. $\boldsymbol{v}_{r,ij}$ is the relative velocity from particle i to particle j, $\boldsymbol{v}_{s,ij}$ is the slide velocity at the impact point. k_n and k_t are coefficients of elasticity in normal and tangential directions, respectively. η_n and η_t are damping coefficients in normal and tangential directions, respectively, which are determined by recovery coefficient e.

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